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Surface Fluctuations of Lake Biwa caused by the Muroto Typhoon

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Abstract

The extraordinary fluctuations of the water of Lake Biwa due to the typhoon on Sept. 21 last year are investigated, and the writer's theory of meteorological tunamis and seiches is applied to them. For the southern shallow portion of the lake, 3.4m deep on average, the fluctuation can almost be explained as that found in the case of "no bottom-friction", so that the bottom-current is not much less than at the surface, while in the northern deep portion of 36.4m depth, the phenomena more nearly resemble the case of "no bottom-current". The coefficient of bottom-friction (assumed linearly proportional to the slip velocity) and the eddy viscosity during the storm are estimated as follows:

	Coef. of friction	Eddy viscosity
Southern part	0.16 c.g.s.	33 c.g.s.
Northern part	3.35	1020

The height of wind-waves on the north coast of the lake are also determined from various kinds of traces left after the storm, and utilised to test Stevenson's and Boergen's experimental formulae. Stevenson's formula seems to include the effect of both wind wave at the coast and the seiche motion, while Boergen's represents merely the wind-wave of progressive nature and consequently half the height of coastal waves when used for the coast of a lake.

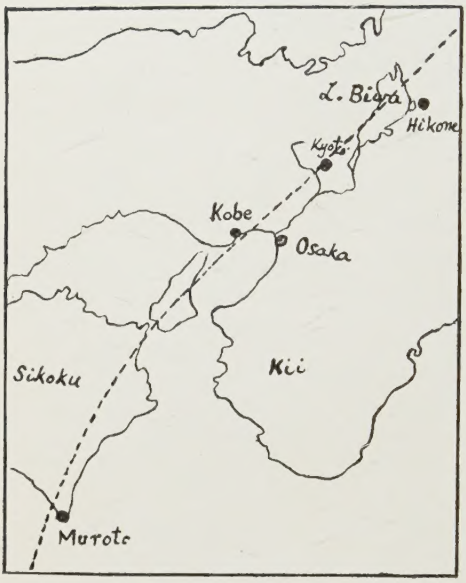
§ 1. Limnograms and other observation-data

The typhoon on Sept. 21 last year, which established a 684 mm world record for deepest central pressure at Cape Muroto in Sikoku, passed close to Lake Biwa between half past 8 and 9 a. m. as shown in Fig. 1. The wind and pressure observed at Hikone Meteorological Observatory, the nearest to the lake, are as shown in Fig. 2.

As a consequence, the surface of the lake water fluctuated abnormally and the oscillations were beautifully recorded on the limnograms at nine stations, six of which belong to the Siga Prefectural office, two to the Osaka Branch Office of Public Works of the Home Office, and one to the Drainage Office of Kyoto. The positions of the stations are indicated in Fig. 3, and the limnograms are reproduced in Fig. 4

Fig. 1

Path of the Muroto Typhoon.

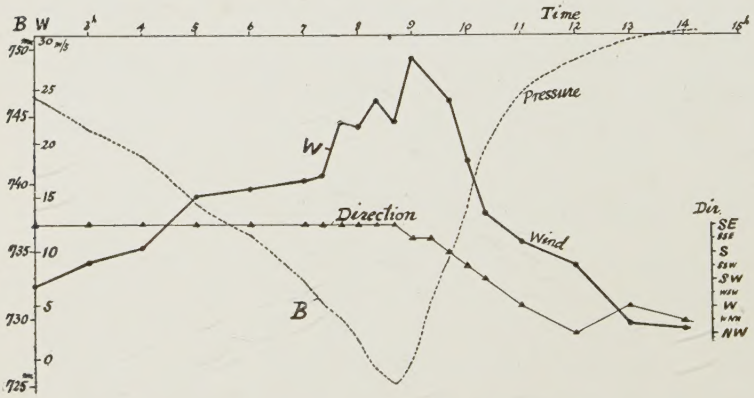


with the permission of the respective offices, for which the writer here expresses his best thanks.

Besides collecting these records, the writer made a week's tour round the lake immediately after the typhoon, inspecting the condition of the limnological stations and the natural features of the coast, and estimating the maximum heights of water reached during the typhoon by such marks as the dust and sand washed up on the dry land, the shore grass swept down in one direction, damaged parts of the coastal road and bank, etc. Special

Fig. 2

Wind and pressure at Hikone.



care was taken to distinguish between the height of the rise of the mean water-level and that of the wind-waves in each locality. The maximum height of the water surface plus wave crest, was investigated at places directly facing the strongest wind in the typhoon, i. e. south; while for the estimation of the rise of mean level only, excluding the wave effect, the traces left by the water were sought on the east- or

Fig. 3
Isobaths of Lake Biwa and limnological stations.

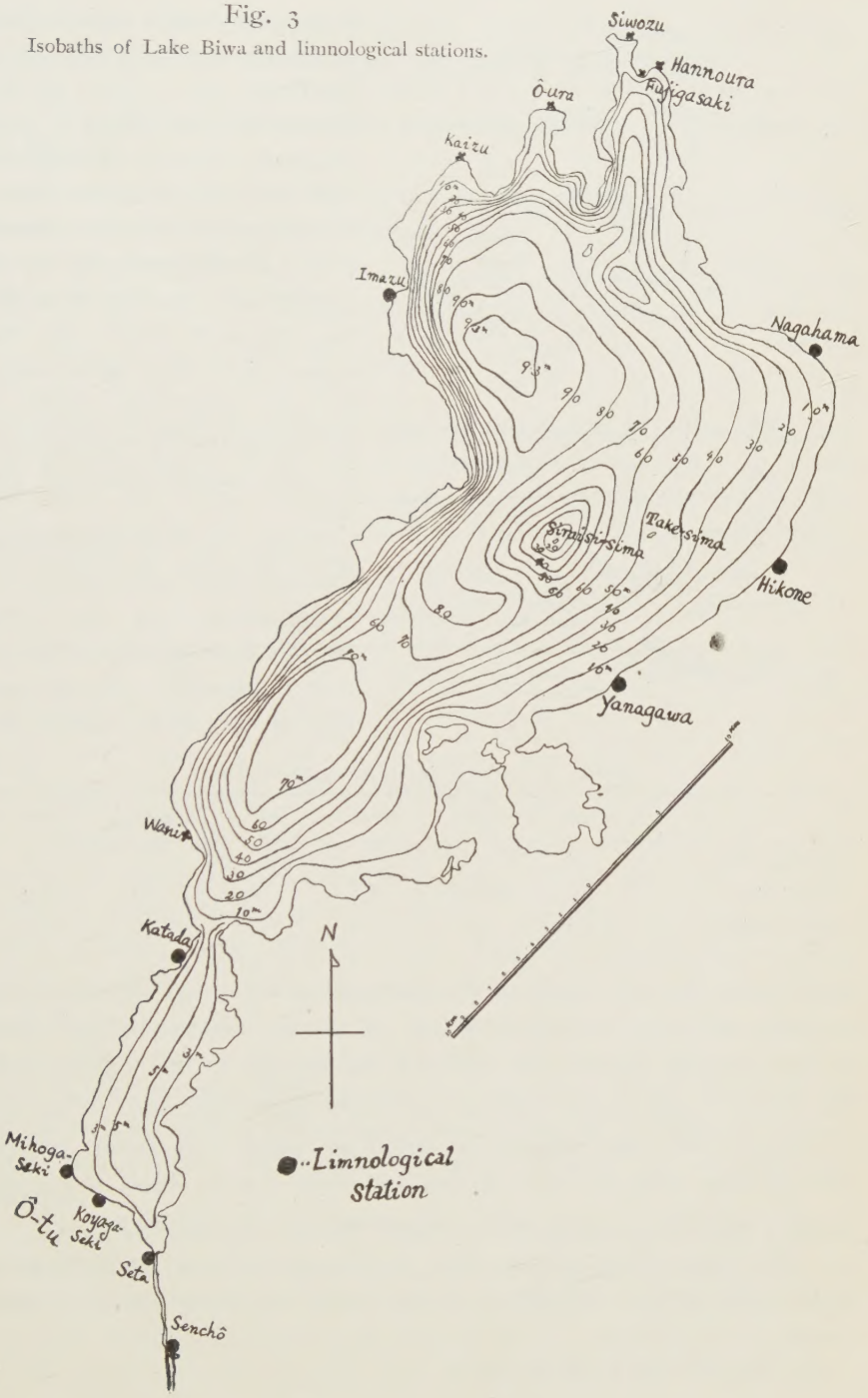
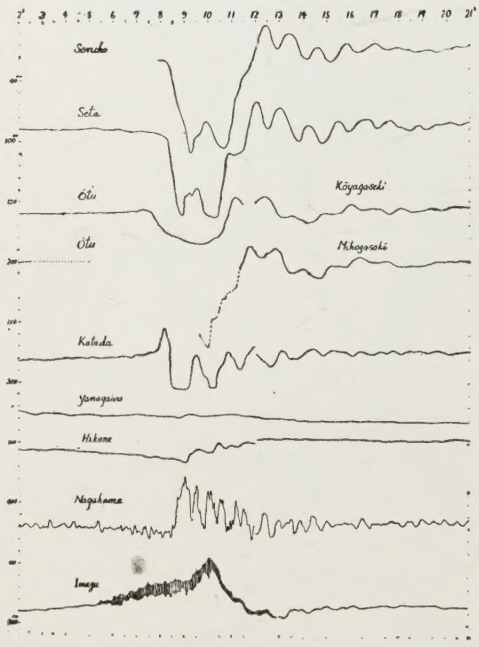


Fig. 4

Limnograms at 9 stations.



west-ward creeks and ditches or on the northern side of a headland, etc. Two of the groups of water-heights thus obtained showed a definite difference from each other, though within each group there was a considerable degree of conformity, proving that the rise of mean level and the wave-height had been satisfactorily separated. Table 1 shows the results of estimation in the northern part of the lake.

The rise of mean level did not differ much at any of these places, but the wave heights were greatest at Kaizu and Fujigasaki. People say that at the latter places the

Table 1 Water rise at the typhoon in m.

	Imazu	Kaizu	O-ura	Siwozu	Fujigasaki	Hanno-ura
Greatest rise	1.8	2.1—2.4	1.2—1.5	1.5—1.8	2.0	1.9
Level rise	0.5	0.6—0.9	0.5	0.3	0.3	0.3
Wave height	1.3	1.8	1.0	1.5	1.7	1.6

spray went over the roofs of the houses, and the writer witnessed two steamers wrecked at Kaizu, which shows the violence of the wind. In the southern portion of the lake, the change in the water-surface due to the typhoon was mainly fall rather than rise, and, of course, no traces other than limnograms could be found, but many persons told me that they had seen, at Ôtu and Seta, a large patch of the lake bottom exposed, a phenomenon unprecedented in history!

The main object of this paper is to explain the above fluctuations of the lake surface in relation to my theory[1] of meteorological tunamis

1. These Memoirs, A, **18**, 201 (1935).

and seiches. As a secondary subject, a test of Stevenson's and Boergen's formulae for wave-heights will also be attempted.

§ 2. Wave heights and the empirical formulae of Stevenson and of Boergen.

Stevenson gives the following empirical formula for wave height, based upon the observations at Scotish lakes, $H=1.51\sqrt{D}+(2.5-\sqrt[4]{D})$, where H denotes the height of wave in feet, and D the fetch windward in nautical miles. On the other hand Boergen's formula for sea waves is

$$H=\frac{Q}{3}\Big/\left(1+\frac{1.86}{t}\right)\left(1+1.86\times 1.94\frac{Q}{D}\right),$$

where Q denotes the wind-velocity in m/sec., t the time in hours after the wind begins to blow, and D is the fetch in sea miles as before, but H is the wave height in metres. In the present case of lake Biwa, measuring the fetch D from a map issued by the Land Survey and taking Q and t from Fig. 2, we get the following table:

Table 2. Calculated wave-heights

		Imazu	Kaizu	O-ura	Siwozu	Fujigasaki	Hanno-ura
D (km)		23	28	18 (30)	31	29	30
H (m)	S	1.83	1.93	1.32 (1.97)	1.99	1.96	1.97
	B	0.57	0.66	0.36 (0.57)	0.58	0.56	0.57

Comparing this with the observed values in Table 1, we see that the value given by Stevenson's formula almost coincides with the observed maximum height of wind-wave plus the rise of mean level which includes seiche effect in turn. That the formula of Stevenson will correspond to water-height of this nature may be easily understood from the original data taken as the basis of its reduction. Such a close coincidence as the above, however, was beyond my expectation, since in the formula both intensity and duration of the wind are left out of consideration. This coincidence perhaps means that the severest storm at any place might be of the same order in its intensity and duration.

Boergen's formula, on the contrary, though it seems very rational in form, is not easy to use because of the difficulty of estimating the duration of the strongest wind of constant value. At any rate, the values in Table 2 are calculated, taking $Q=23$ m/s and $t=2.5$ hours for SE wind, and $Q=25$ m/s and $t=1.5$h for S wind. The figures

obtained appear unexpectedly small at first sight, being only about one half the observed wave-height separated from the rise of mean level or seiche effect. Reconsideration, however, shows that in reality the coincidence is not so bad. Probably Boergen's formula is suitable for progressive waves in a sea far away from the land, but not for waves of stationary character on a leeward coast and consequently doubly amplified by reflection.

§ 3. Several periods and damping of the surface-fluctuations

Now apart from the wind waves considered above, let us investigate the surface-oscillations for longer periods recorded on the limnograms.

Various periods:—From Fig. 4, we observe that oscillations with periods of about 4.1 and 1.14 hours are most noticeable.

(1) Oscillation of period 4.1 h = 250 min. developed conspicuously in the southmost region only, where the first fall of level reached 70 cms or more; but at Katada it was very slight, and in the northern main body of the lake only a trace, if any, could be detected. Its phase is obviously the same everywhere in the oscillating portion south of Katada, and its amplitude increases as it moves towards Seta. These facts, together with the topography and the isobaths of the lake, show that this undulation of four hour period may be a fundamental oscillation of the southern shallow part as a *bay*, whose mouth, and consequently node, lies a little north of Katada.

(2) Oscillations of 1.14 h = 68.4 min. are next conspicuous both in the southern and northern parts of the lake. The amplitude is greatest at Seta and Nagahama, and falls to about half at Katada and Ôtu and becomes very small at Hikoné and Imazu. At Yanagawa, almost half-way between Nagahama and Katada, the oscillation almost vanishes. The phase is the same at Katada and Seta on the one hand, and at Nagahama, Hikoné and Mihogasaki on the other. The two groups are in opposite phase. Thus it seems to me that the oscillation of about 70 minutes is the primary oscillation of the long elliptic deep basin between Nagahama and Katada, and that the oscillation in the southern shallow portion must be a secondary one excited by the action of the main body.

Besides the above widely distributed oscillations, the following local oscillations may be noticed.

(3) Oscillations of 20 to 30 and 12 min. occur, strongly marked, at Nagahama, also at Imazu though here much feebler in intensity.

The oscillating area is perhaps the rectangular basin between Nagahama, Imazu, Siraisi islet and Takesima.

(4) An oscillation of about 5 min. period is conspicuous at Imazu. The corresponding oscillating area seems to be the "shelf" of lake, but the decision will be reserved for future investigation.

For later informations, let us here add briefly the habit of fluctuation at the places under considerations, examining the limnograms for the past ten years which we owe to the courtesy of the Siga Prefectural Office.

(a) On the Ôtu side of the lake, once or twice a month oscillations of 4 hour and also of 70 min. period occur with amplitude up to 5 cms.

(b) At Hikone and Yanagawa, especially at the latter, the limnograms is very monotone, seiches of amplitude greater than 10 cms being very rare.

(c) Nagahama is very sensitive to seiches, and the amplitude of the seiche attains 20 to 30 cms for a few days every month.

(d) At Imazu, notwithstanding its situation at the head of the lake, the limnogram is, contrary to expectation, usually the most monotone in the lake. The amplitude has never exceeded 4 cms for 10 years except in the Muroto typhoon, so that the limnograph of 1/20 reduction draws only a straight line every day, merely widening the line occasionally. This fact will be very important in the discussion of the fundamental oscillation of the main body of the lake.

Damping factors:—We next turn to the damping of the level fluctuations caused by the Muroto typhoon.

Measuring the successive crests and furrows for the two principal oscillations of 4.1 and 1.14 hour period, we get the following table of damping factor i. e. the ratio of the successive amplitudes.

Table 3. Damping factor and index

(A) Damping per half period of the 4.1 hour oscillations

Station	Senchô	Seta	Kôyazeki	Mihogasaki	mean	Index $\frac{1}{2}\nu\beta_0^2$
						sec.$^{-1}$
After storm	0.566	0.524	0.511	0.520	0.530	8.85×10^{-5}
During storm	0.125	0.149	—	0.100	0.134	2.73×10^{-4}

(B) Damping per one period of the 70 min. oscillations i. Southern part of the lake

Station	Senchô	Seta	Kôyazeki	Mihogasaki	Katada	mean	Index $\frac{1}{2}\nu\beta_0^2$
Damp. factor	0.762	0.747	0.822	0.741	0.707	0.756	6.82×10^{-5}

ii. Northern main body of the lake

Station	Nagahama	Hikone	Katada	mean	Index $\frac{1}{2}\nu\beta_0^2$
Damping factor	0.750	0.702	0.707	0.720	8.05×10^{-5}sec.$^{-1}$

The damping index is also calculated. This term signifies the index when the damping factor is considered as an exponential function of time, $e^{-\frac{1}{2}\nu\beta_0^2 t}$, as was explained in our theoretical paper[1] on meteorological tunamis and seiches. From the table we notice that:

(1) The damping of the oscillation of 70 min. period is much less in the southern shallow part than in the northern deep portion. This will suggest the origin of the oscillation in the southern portion, as will be explained later.

(2) The damping index in the southern part is three times greater during the storm than after. This agrees roughly with the fact that the eddy viscosity ν varies with the velocity of current. For, the largest change of level till noon is $70+20=90$ cms in half a period, while in the afternoon a level-change of 30 cms maximum occurs in half a period. Thus the current of water, being assumed proportional to the level change in the same interval of time, will be in the ratio $90:30=3:1$ during and after the storm.

§ 4. The nature of the oscillation of 4.1 h period and its development

Since the oscillation of 4.1 hour period occurs only in the southmost part of the lake, it must clearly be a vibration of the southern part of the lake. Now, what is the nature of this vibration? To answer this question, let us refer to the formulae of the proper period of a closed canal and a bay.

For a rectangular *lake* of length L and of depth H, the period of its free vibration of mth order is usually given by

$$\text{period}=2\pi/\sigma=2\pi/\sqrt{gH(m\pi/L)^2}, \qquad \cdots\cdots\cdots\cdots(1)$$

which is derived for an ideal fluid with "no bottom-friction" and disregarding the earth's rotation. According to Proudman[2] and also to the writer[3], the action of the earth's rotation $\bar{\omega}$ will change the formula as below:

$$\text{speed}=\sigma=\sqrt{gH(m\pi/L)^2+4\bar{\omega}^2}. \qquad \cdots\cdots\cdots\cdots(2)$$

1. loc. cit. 2. M. N.R. A. S. Geophys. Suppl. **2**, 197 (1929), eq. (3.42).
3. These Memoirs, A, **17**, 249 (1934), eq. (17).

Numerical test will show, however, that the rotation-effect can be neglected for an ordinary lake or bay. In the case of a viscous fluid with bottom-friction, the writer's formula[1] is

$$\left.\begin{aligned} &\sigma=\sqrt{B_0\frac{g\sin\beta_0 H}{\beta_0}\left(\frac{n\pi}{L}\right)^2-\left(\frac{\nu_1\beta_0^2}{2}\right)^2}, \\ &\text{where } B_0=\frac{2(\beta_0^2+h^2)\sin\beta_0 H}{H(\beta_0^2+h^2)+h}\cdot\frac{1}{\beta_0},\quad \beta_0\tan\beta_0 H=\frac{f'}{\nu}\equiv h,\quad \nu\equiv\frac{\mu}{\rho} \end{aligned}\right\}\quad(3)$$

and μ denotes the viscosity, ρ the density and f' the coefficient of friction at the water-bottom. The viscosity term in the radical will commonly be negligible for small oscillations, but if the disturbance of water is considerable as on a stormy day, the eddy viscosity becomes so marked as to lengthen the period and in extreme cases will even make the motion non-periodic.

For a *bay* of length L', we can use the above formula, only putting $L=2L'$ and applying the so-called "mouth correction".

Now let us return to the problem of oscillation of the southern part of lake Biwa. Seeing that the 4.1 h oscillation is most conspicuous at Seta while almost vanishing at Katada and that both the depth and breadth of the water basin abruptly change at a point slightly north of Katada, it is obvious that the oscillation is of the nature of *bay*-oscillation.

As to the mouth and head of the bay, we may consider the following four cases from Fig. 3, of which isobaths are drawn after a report[2] of the Kobe Marine Observatory on a map issued by the Military Land Survey.

Table 4. Possible areas of oscillation as a bay

	Bay mouth	Bay head
I	Narrowest point north of Katada	Top of River Seta
II	„	Obliquely along Ôtu city
III	Line through Wani	Top of River Seta
IV	„	Obliquely along Ôtu city

Measuring the length L', breadth B and mean depth H for each oscillating area, we get Table 5.

1. These Memoirs, A, **18**, 201 (1935), eq. (39). 2. 海洋氣象台彙報 第八號 大正十五年。

Table 5. Data of the supposed areas of oscillation

	L'	B	H	L'/B	Mouth correction	Period	$L'/H\propto\zeta$
	km	km	m			h	
I	17	3.3	3.4	5.15	1.16	3.78	5.0
II	15	„	„	„	„	3.34	4.41
III	20	3.7	3.98, 3.83	5.34	1.155	4.08	5.25
IV	18	„	4.05, 3.88	„	„	3.65	4.65

The basin south of Katada is nearly of uniform depth and hence the simple arithmetical mean can be taken as the mean depth for all ordinary purposes; but since north of Katada the depth increases abruptly, in cases III and IV we should take the inverse-square-root-mean for the period-calculation and the inverse-mean for the calculation of level rise. The double values of H (III and IV) in the table have this significance. "Period" is calculated by eq. (1) with mouth correction. All these modes are probably possible in reality, depending on circumstances; for, on the limnograms during 10 years the actual period is found to change within a range of 30 minutes according to days. To which of the four modes does the extraordinary oscillations at the recent typhoon then belong?

By trials of the period and the level rise, the first mode appears as the most probable for the recent great fluctuations.

Now, in order to estimate the effect of the viscosity upon the period of oscillation, let us first compare the observed speed σ_{obs} with the ideal speed σ_0 of an ideal fluid.

$$\sigma_{obs}=2\pi/(4.1\times 3600)=4.25\times 10^{-4},\qquad \sigma_0=2\pi/(3.78\times 3600)=4.6\times 10^{-4},$$

$$B_0\frac{\sin\beta_0 H}{\beta_0 H}=\frac{\sigma_{obs}^2+[\nu\beta_0^2/2]^2}{\sigma_0^2}=\frac{4.25^2+0.88^2}{4.6^2}=0.89.$$

Progress of the level-fluctuations:—The intensity of wind or barometric gradient may be represented by the steady value of level rise, $\bar{\zeta}$, which would be attained in a very long time if the motive force remained constant. For the wind of velocity Q, the tracting force is

$T=3.2\times 10^{-6}\,Q^2$ in c. g. s. units.

$$\left.\begin{aligned}&\bar{\zeta}=\int n\frac{T.dL}{g\rho(H+\zeta)},\qquad n=\frac{1+\frac{1}{2}f'H/\nu}{1+\frac{1}{3}f'H/\nu}\quad\text{for wind,}\\ &\text{and}\\ &\bar{\zeta}=\int\gamma_0 dL\qquad\text{for barometric action,}\end{aligned}\right\}\qquad(4)$$

where n is a coefficient of value 1 (for no bottom-friction) to $3/2$ (no bottom-slip), and γ_0 denotes the barometric gradient in water column. When the motive force, and hence $\bar{\xi}$, varies with time, the level rise ζ at any time t after the commencement of the action will be given by our formula[1]

$$\zeta_m(t)=\int_0^t \frac{\partial}{\partial\tau}\bar{\xi}_m(\tau)\left[1-\frac{\sqrt{4\sigma_m^2+(\nu\beta_0^2)^2}}{2\sigma_m}\cos\{\sigma_m(t-\tau)-\varepsilon\}\right]d\tau. \quad (5)$$

where the suffix m means the order of component fluctuation.

Now since we have wind-records along the lake only at Hikone, we must necessarily assume that the wind of the recent typhoon over the part of the lake under consideration is everywhere the same as at Hikone, though acting 20 min. earlier. Using this approximation we calculate first the component of T along the longitudinal axis (N 20° E) of the basin, and then obtain $\bar{\xi}$ at Seta for the wind (Fig. 5). Add to this a correction for the barometric depression. For a lake of small dimension compared with the range of low pressure, the barometric effect upon the lake-level will naturally be far smaller than in an open sea where the water-supply is unlimited, and it will be sufficient to estimate roughly from the weather charts drawn at each hour or half-hour. In the present case the barometric effect does not exceed 5% of the wind effect. Substituting the total $\bar{\xi}$ in eq. (5), we calculate $\zeta(t)$ by mechanical integration. Table 6 shows a part of the calculations for the period from 6 a. m. to 2 p. m.

Table 6. Calculation of level change at Seta, taking $n=1$.

t	6h	7	8h			9			10		11	12	13	14h
			0m	20	40m	0	20	40	0	20				
Q (m/s)	16.0	16.5	21.5	23.0	22.0	28.0	—	24.0	18.0	13.5	11.1	8.4	3.5	3.0
Direction	SE	SE	SE	SE	SE	SSE	SSE	S	SSW	SW	W	NW	W	WNW
$\bar{\xi}_1$ for Wind	7.3	7.8	13.2	17.0	15.7	76.4	65.4	95.7	60.3	25.6	2.4	1.9	0.2	1.5
$\bar{\xi}_1$ „ Press.	−1.5	−3.2	−2.8	−2.9	0	4.0	4.1	4.2	4.4	3.5	1.8	0	0	—
Total $\bar{\xi}_1$	5.8	4.7	10.4	14.1	15.7	80.4	69.5	99.9	64.7	29.1	4.2	1.9	0.2	1.5
ζ_1 (cm)	**0**	**0.8**	**1.4**	**3.9**	**4.4**	**10.6**	**31.4**	**56.5**	**72.7**	**72.5**	**28.5**	**−10.1**	**−12.6**	
$\bar{\xi}_2$	0.6	0.5	1.2	1.4	1.6	9.2	7.8	11.0	6.8	3.2	0.5	0.2		
ζ_2 (cm)	**0**	**0.3**	**0.9**	**0.6**	**0.4**	**3.4**	**14.5**	**10.3**	**4.9**	**4.3**	**−2.9**	**−1.5**	**0**	

In Fig. 6 we plot the values of ζ_1 thus obtained and see that they agree with the actual fluctuations in general run. The superposition

1. These Memoirs, A, **18**, 201 (1935).

of ζ_3 on ζ_1 makes the first fall of level a little earlier, but does not modify the general features of the limnographic progress.

Fig. 5

Wind at Hikone and corresponding $\bar{\xi}$ for several places.

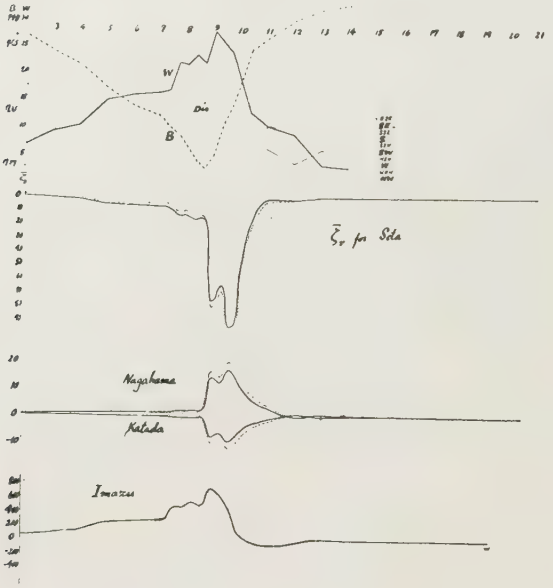
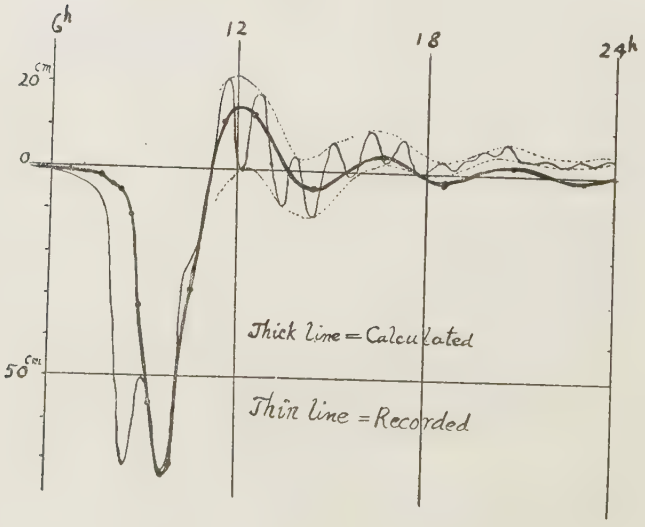


Fig. 6

Calculated level change at Seta, taking $n=1$.



We here attach a similar calculation using the wind-data at Senchô situated in the valley of Seta gorge. For topographic reasons, the latter cannot be extended to the later period of the typhoon, but it is very suggestive for the initial stage of the fall of level.

Table 7. Initial stage calculated from the wind-data at Senchô

Time	7^h		8						9^h		
	30^m	40	0	10	20	30	40	50	0	20	40^m
Comp. Q^2	19.7	19.0	26.5	69.5	181.0	489.0	431.0	175.0	89.1	36.7	2.3
ζ_1 (cm)	0		2.1			12.8			72.2		40.7

§ 5. 70 min. period oscillation.

This oscillation appeared not only in the southern part but also in the main body of the lake.

Nature of the oscillation:—In the northern section, we notice (a) the greatest amplitude, though in opposite phase, at Katada and Nagahama, (b) no oscillation at Yanagawa, (c) a small oscillation at Hikone and Imazu. These facts show that the corresponding oscillating area is the elliptical basin between Katada and Nagahama. By actually measuring the depth at each tenth of the longitudinal axis and calculating the various means as in table 8, we get the period 71.4 min.

Table 8. Depth of the basin from Katada to Nagahama

No.	Depth H	$1/\sqrt{H}$	$1/H$	$\Sigma(\Delta L/H)$
1	7.32^m	0.2770	0.0770	0.0385
2	24.6	0.2015	0.0406	0.0794
3	33.3	0.173	0.0300	0.1091
4	41.2	0.156	0.0243	0.1334
5	39.1	0.160	0.0256	0.1590
6	48.8	0.143	0.0205	0.1795
7	47.8	0.145	0.0209	0.2004
8	53.6	0.137	0.0186	0.2190
9	42.1	0.154	0.0237	0.2427
10	29.6	0.184	0.0336	0.2763
11	0			0.447 (half remained)
Mean depth	36.37^m	29.1^m	22.4^m	

The bent area extending to Imazu also has a period of the same order,[1] but the oscillation here appears irregular, as explained in § 3.

1. Mr. Suda gives the period=71.8 min. for between Wani and Imazu.

Then what will be the nature of the oscillation in the *southern* part of the lake? Some will take it to be a harmonic oscillation of the southern basin itself, and sometimes such a harmonic oscillation may really take place, but the writer considers it to be forced oscillation excited by the primary oscillation of the northern main body and on this particular occasion at least it can not be harmonic.

The reasons are as follows:

(1) The period of 70 min. is numerically 1/3.5 of 4.1 hours, but not 1/3.

(2) The 70 min. oscillation is very large at Katada where the fundamental vibration of 4.1 h period has its node.

(3) As shown before, the third harmonic oscillation calculated from the wind of the typhoon is decidedly small, while the real amplitude of 70 min. oscillation in the afternoon is very large, rather greater than that of the 4.1 h oscillation.

(4) The phase is the same at Seta and Katada but opposite at Mihogasaki.

(5) Damping is less for the 70 min. oscillation in the southern portion than in any other oscillation, as already explained.

Thus the 70 min. oscillation in the southern part resembles the derived tide in a bay excited by the outside ocean-tide, or the joint oscillation in a two-step basin dealt with by Proudman.[1]

Amplitude-ratio:—This oscillation has the largest amplitude of 30 cm at Nagahama, but 20 cm at Katada. The difference is due to the distribution of water-depth. The change of depth from Katada to Nagahama is given in Table 8, and the last column of the table corresponds to the values of $\bar{\xi}$ above the level of Katada, taking $L.\ T/g\rho$ as unity. Fig. 7 shows the profile of the basin and the amplitude-ratio

Fig. 7

Profile of the section from Nagahama to Katada.

1. loc. cit.

of the oscillation there. The difference of levels at Nagahama and at Katada being 44.7 units, we see that:

Level fall at Katada : Level rise at Nagahama = 16.5 : 28.2,

which nearly coincides with the actual ratio.

Time-relation of the level fluctuation:—In the same manner as in § 4, we calculate the change of level in the oscillation area under consideration due to the Muroto Typhoon. Assuming that the wind all over the region is the same as at Hikone, and taking $n=3/2$ and the axial direction of the oscillation area = N 50° E, Table 9 and Fig. 8 are obtained.

Table 9. Level fluctuation in the northern main body

(A) At Nagahama

t	6^h	7	8			9			10		11	12	13^h
			0^m	20	40	0	20	40	0	20^m			
Wind Q	16.0	16.5	21.5	23.0	22.0	28.0	—	24.0	18.0	13.5	11.0	8.4	3.5
Dir.	SE	SE	SE	SE	SE	SSE	SSE	S	SSW	SW	W	NW	W
ξ for Wind	1.2	1.4	2.3	2.5	2.4	20.2	17.6	24.7	17.7	10.0	4.5	−0.3	0.4
ξ for Press.	−1.2	−1.6	−1.3	−1.1	0	2.0	2.3	2.7	3.0	2.0	1.0	0	0
Total ξ (cm)	0	−0.2	1.0	1.4	2.4	22.2	19.9	27.4	20.7	12.0	5.0	−0.3	0.4
ζ (cm)	0	−0.6	1.2	1.1	1.3	10.2	41.5	30.8	16.3	21.0	−4.5	−6.1	

(B) At Katada

t	6	7	8			9			10		11	12	13
			0	20	40	0	20	40	0	20			
ξ f. Wind	0.75	0.8	1.4	1.5	1.4	11.8	10.2	14.4	10.4	5.8	2.5	−0.2	0.3
ξ f. Press.	−0.8	−1.6	−1.4	−1.5	0	2.0	2.0	2.1	2.2	1.8	0.9	0	0
Total ξ (cm)	0	−0.8	0	0	1.4	13.8	12.2	16.5	12.6	7.6	3.4	−0.2	0.3
ζ (cm)	0	−1.5	0.7	1.1	2.2	9.6	29.4	19.3	11.5	16.2	−8.4	−4.2	−1.9

The writer believes that he has thus explained the essential features of the mechanism of surface fluctuation in the northern portion.

Next, as to the oscillation of the same kind in the southern basin, it is sufficient to consider it relatively to that at Katada. Now, the depth of the basin south of Katada is only about one tenth of that in the northern main part, and the whole lake forms a two-step basin. According to Proudman[1], the co-oscillation of such a two-step basin will be given by

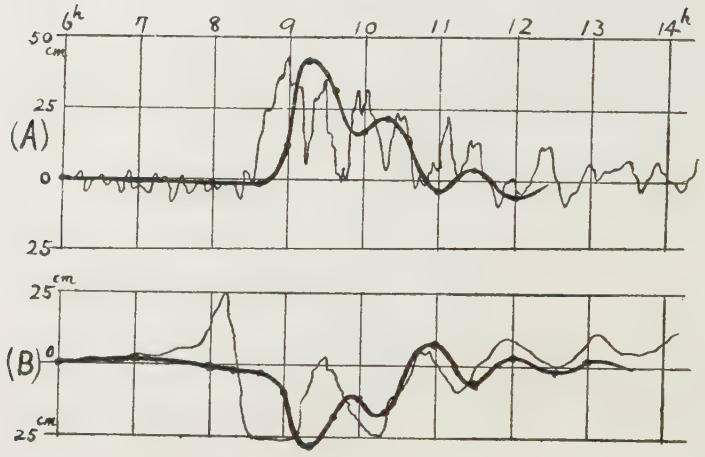
$$\zeta = Z \cdot \frac{\cos k'(x-L')}{\cos k'L'} \cdot \sin(\sigma t + \alpha), \qquad k' = \frac{\sigma}{\sqrt{gH'}} \qquad (6)$$

1. loc. cit.

Fig. 8

Level change calculated and recorded on limnogram

(A) Nagahama

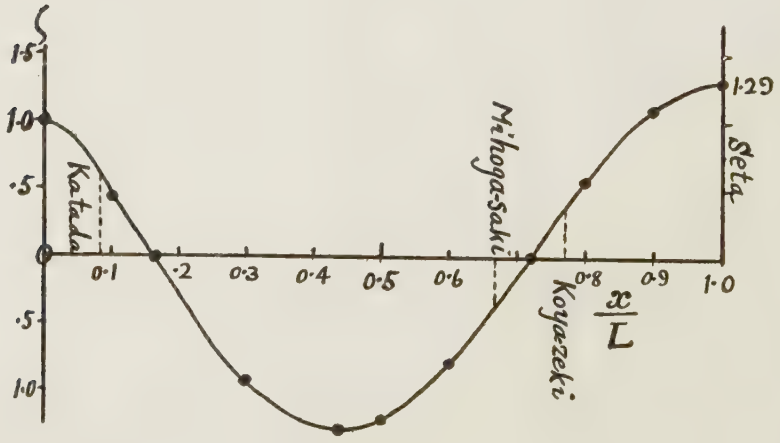


(B) Katada

in the shallower portion of length L' and depth H', if the main part is very deep compared with the portion considered. This equation exactly coincides with the formula for derived tide in a bay given by Harris[1] or Defant[2]. In the eq. the origin of coordinates is taken at the place of abrupt change of depth or the bay-mouth, and x is measured horizontally towards the other end of the region. In the

Fig. 9

Relative amplitude at several sections



1. Manual of Tides, IV (1900), p. 681. 2. Ozeanographie (1929), p. 193.

present case, the above formula gives the amplitude-ratio at ten sections as shown in Fig. 9.

This diagram will explain the phase relation between Katada, Mihogasaki and Seta. The great amplitude at Seta is partly due to this action, though mainly accelerated by the contraction of the section near the bay head.

§ 6. Characteristic general rise of level at Imazu, etc.

We shall here describe some notable points left untouched as yet.

(1) At Imazu, besides the short-period oscillations, a characteristic general rise of non-periodic nature is conspicuous. Comparing this with the universal fall at Nagahama, Hikone and Yanagawa in the early morning up to 8 a. m., we may conclude that the general rise at Imazu is due to the accumulation of water from the opposite eastern coast of far wider extent, and also to the passing of the center of the typhoon almost directly over Imazu. (cf. the last curve in Fig. 5).

(2) At Katada, the very first stage of level-change was elevation, notwithstanding its situation near the mouth of the "bay". This fact shows how severe the drift of the wind was during the typhoon, and how great a hindrance was formed even by the slight contraction of section north of Katada.

(3) After the storm, the whole lake shows a gradual increase in level amounting to a few cms. This is of course due to the precipitation accompanying to the typhoon.

§ 7. Estimation of μ and f', etc.

From the actual values of the three quantities, the damping factor, the oscillation period and the maximum ζ, we can estimate three other quantities, ν, f' and β_0.

(A). *In the southern portion of the lake* ($H=3.4$ m) :—Since the max. fall of level in the southern basin nearly corresponds to

$$n \equiv \left(1+\frac{1}{2}\frac{f'\rho H}{\mu}\right)\Big/\left(1+\frac{1}{3}\frac{f'\rho H}{\mu}\right) \fallingdotseq 1,$$

$f'\rho H/\mu$ must be very small, and the condition for β_0 in eq. (3) gives $f' \fallingdotseq 2H\cdot(\frac{1}{2}\nu\beta_0^2)$.

Putting the actual value of the damping index $\frac{1}{2}\nu\beta_0^2$, we get

$f' = 2\times 340\times 2.73\times 10^{-4} = 0.16$ c. g. s. during the storm

$= 2\times 340\times 0.885\times 10^{-4} = 0.06$ after the storm.

Next, from the actual and the ideal period we have

$$0.89 = B_0 \frac{\sin \beta_0 H}{\beta_0 H} = \frac{2(1+\tan^2 \beta_0 H)}{1+\tan^2 \beta_0 H + \tan \beta_0 H / \beta_0 H} \left(\frac{\sin \beta_0 H}{\beta_0 H} \right)^2,$$

which gives $\beta_0 H = 1.38$, or $\beta_0^2 = 1.65 \times 10^{-5}$.

Now since obviously $\nu = \frac{2}{\beta_0^2} \times$ damping index (i. e., $\frac{1}{2}\nu\beta_0^2$), we have

$\nu = 2.73 \times 10^{-4} \times 2 / 1.65 \times 10^{-5} = 33$ c. g. s. during the storm
$= 0.885$,, ,, $= 11$ after the storm.

(B) *In the northern main body of the lake* ($H = 36.4^{m}$) :—Here the most appropriate value of n is 1.4, which corresponds to $f'\rho H/\mu = 12$. From the relation $\beta_0 H \tan \beta_0 H = f'\rho H/\mu = 12$, there results

$\beta_0 H = 1.45$, $\beta_0 = 1.45/3640 = 3.98 \times 10^{-4}$ cm^{-1},

which again gives

$$\nu = \frac{2}{\beta_0^2} \times \text{damping index} = 2 \times 8.05 \times 10^{-3} / (3.98 \times 10^{-4})^2 = 1020,$$

and $$f' = 12 \frac{\nu}{H} = 3.35 \text{ c. g. s.}$$

The writer here expresses his cordial thanks to the Hattori Hôkô-kwai for the grant with which the present research has been carried out.

A Theory of the Annual Variation of Temperature of Ocean or Lake

By Tadao Namekawa

(Received July 27, 1935)

Abstract

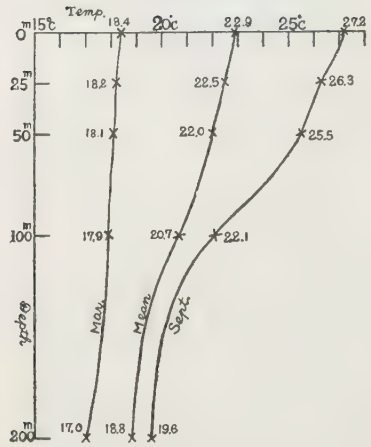
It may be admitted that the chief controlling factor of the annual variation of temperature of ocean or lake is eddy convection, but it is very doubtful whether it will satisfy, as has been believed until recently, the simple diffusion-equation. The problem is elucidated when the transfer of heat is taken into consideration, i. e., when the occurrence of instability in the cooling stage, and the vertical transfer of heat at the time of its disappearance are taken into account. For this purpose, adopting L. F. Richardson's view that the equation varies according as an instantaneous value or a mean value of the temperature is taken, and regarding our observed temperatures as showing mean values, the writer has found a new form for the diffusion equation, that is as near to perfection as possible, and, comparing his solution with actual examples, he found that his new theory was justified. Thus the author believes that this theory has brought the physical explanation of this subject to completion, and has also thrown a light on the method of reduction of the records of the observed water-temperature.

I. General Consideration

Many scientists are of the opinion that eddy convection is the main factor controlling the actual distribution of water-temperature in the layer which is subject to annual variation. The researches of H. Jeffreys[1] and J. E. Fjeldstad[2] were made from this point of view. W. Schmidt,[3] though of the same opinion, noticed that, contrary to his expectation that better results would be obtained from annual variation than from daily variation, the results from the former were rather worse. These investigators carried on their work on the supposition that the eddy equation has the form $-\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(k\frac{\partial\theta}{\partial z}\right)$ in the usual notation. A certain measure of agreement between the actual observation and the theory concerning the distribution of temperature may be arrived at by the application of the above equation with certain appropriate conditions. But, when the transfer of heat is considered,

1. Phil. Mag. **39**, 578 (1920). 2. Geofys. pub. **10** No. 7.
3. Der Massenaustausch in freier Luft.....SS. 30–33.

Fig. 1



a contradiction will be met with. If the above diffusion equation is valid, the annual variation of the water-temperature ought to be of the same nature as that of the ground-temperature. Whereas, as shown in Fig. 1, the vertical distribution of the annual mean temperature of ocean or lake is not uniform as that of the ground-temperature is, but higher in the upper layer. Moreover, this annual mean temperature is to be regarded as the temperature in a steady state. If the state is steady, heat must be transmitted permanently from the upper to the lower part of the water. No evidence is found of this transmission, at least not in ocean or lake in the temperate zone. And, from a theoretical point of view, such a state, although not impossible, presupposes a somewhat extraordinary structure. In fact, it is most reasonable to suppose that the heat is carried down from the upper layer of water to the lower during the warm half-year and that the reverse process occurs during the cold half-year, the total exchange of heat flux, coming in the end to zero for the whole year. Thus, in the cooling stage, there must be an upward flux of heat. Then, according to the generally accepted theory, since the eddy flux of heat is $-k\frac{\partial\theta}{\partial z}$, the distribution of temperature in the winter season must generally show $\frac{\partial\theta}{\partial z}>0$ (z: positive downward); while actual observations give $\frac{\partial\theta}{\partial z}<0$ (though very near zero) in this stage. In the case of the ground-temperature, the theory and the actual state agree very well. Why, then, should the above mentioned contradiction be found in the case of water temperature? It is clear that the transfer of heat is not due to the eddy convection alone. Direct radiation has its effect, but this effect is limited to the surface layer, and to a very small portion of the whole layer subject to annual variation. Hence its influence may give a little correction only for the thin uppermost layer, but it cannot obliterate the doubt above stated in so far as the main body of water is concerned. Now, the reason why $\frac{\partial\theta}{\partial z}>0$ does not apply is clear, since $\frac{\partial\rho}{\partial z}<0$ (ρ:

density of water) means instability, and generally $\frac{\partial \rho}{\partial z} \lessgtr 0$ according as $\frac{\partial \theta}{\partial z} \gtrless 0$. To make matters simpler, our discussion will be confined to cases where $\frac{\partial \rho}{\partial z}$ and $\frac{\partial \theta}{\partial z}$ have the relation above given. The generality of the problem may be preserved by making a slight alteration in our estimate according to the difference of relation. In the cooling stage, $\frac{\partial \theta_i}{\partial z} > 0$ for some time, but, this state, being unstable, cannot last long. Intense mixing must occur immediately, subsiding into the state $\frac{\partial \rho}{\partial z} = 0$, that is, $\frac{\partial \theta}{\partial z} = 0$. This is confirmed by actual observation (in regions near the water surface). It must be noticed, however, that heat is carried spontaneously upwards in this process. Since, during the intense mixing, k_i has a rather large value, and $\frac{\partial \theta_i}{\partial z} > 0$, a considerable quantity of heat is carried upwards. This process may also be considered as an eddy convection, if we use the instantaneous values of θ_i and k_i and express the eddy equation as $\frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left(k_i \frac{\partial \theta_i}{\partial z}\right)$. The data which the author is going to treat are, however, of a different nature. They are either a *monthly mean temperature* or a temperature observed on a particular day which may be adopted as the *mean* for the month concerned. Such being the case, if we use the ordinary equation $\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial \theta}{\partial z}\right)$ with the mean values of both θ and k, what has just been stated about the eddy convection due to instability is not allowed for anywhere in the equation.

L. F. Richardson[1] expresses a similar opinion in his study of the atmospheric eddy. Starting from $\frac{\partial \theta_i}{\partial t} = -\frac{\partial}{\partial z}\left(k_i \frac{\partial \theta_i}{\partial z}\right)$, and putting $\theta_i = \theta + \theta'$, $k_i = k + k'$, he gets $\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial \theta}{\partial z} + \overline{k' \frac{\partial \theta'}{\partial z}}\right)$. Here, θ and k are the *monthly mean values* of θ_i and k_i respectively, and $\overline{k' \frac{\partial \theta'}{\partial z}}$ is the *monthly mean value* of $k' \frac{\partial \theta'}{\partial z}$. The last term means the flux of heat occurring when instability disappears. There is no doubt, of course, of the existence of the process just described. It has, hitherto, been treated as a thermal transfer due to convection—whether regular convection or eddy convection has not yet been made clear. Nor has

1. Weather Prediction. pp. 87–88.

any scientist discussed its nature, so far as the author knows. What will be the value of this quantity, $\overline{k'\frac{\partial\theta'}{\partial z}}$? It is not easy to find. Here we are brought to an impasse, as L. F. Richardson says. To get out of this difficulty, the author is obliged to make a rather bold assumption, upon whose basis he frames up the problem in a practical form which leads to a solution. Comparing the solution with actual example, he wants to show that his theory can explain the real nature of the actual variation of temperature in ocean or lake.

2. The Problem and its Solution

(i) As the equation of eddy convection, we take $\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\cdot\left(k\frac{\partial\theta}{\partial z}+\overline{k'\frac{\partial\theta'}{\partial z}}\right)$ where θ is the monthly mean temperature, t the time, z the depth from the water surface and k the eddy diffusivity, and we consider the most simple case when $k=$const. (independent of t and z).

(ii) For the unknown convection term due to the rapid mixing process occurring when the instability of the layer happens in the cold season, we boldly assume as follows:

$\overline{k'\frac{\partial\theta'}{\partial z}}=qe^{-\alpha z}\varphi_1(\omega t)$ where q and α are constants, and

$\varphi_1(\omega t)=\sin\omega t$ when $0<\omega t<\pi$

$=0$ when $-\pi<\omega t<0$,

the time origin being taken at the autumnal equinox.

$$\varphi_1(\omega t)=\frac{1}{\pi}\left\{1+\frac{\pi}{2}\sin\omega t-\frac{2}{2^2-1}\cos 2\omega t-\frac{2}{4^2-1}\cos 4\omega t-\cdots\cdots\right\}$$

$\omega=\frac{2\pi}{T}=\frac{2\pi}{365\times 24\times 60\times 60}\fallingdotseq 2\times 10^{-7}$ where T is the period (one year).

(iii) For the surface condition, we take $-k\frac{\partial\theta}{\partial z}\Big|_{z=0}=q\varphi_2(\omega t)$

where $\varphi_2(\omega t)=0$ when $0<\omega t<\pi$

$=\sin\omega t$ when $-\pi<\omega t<0$

$$\varphi_2(\omega t)=\frac{1}{\pi}\left\{1-\frac{\pi}{2}\sin\omega t-\frac{2}{2^2-1}\cos 2\omega t-\frac{2}{4^2-1}\cos 4\omega t-\cdots\cdots\right\}$$

(iv) $\theta=\theta_0$ at $z\to\infty$ (bottom condition).

(v) $\theta(t, z)=\theta(t+T, z)$ (stationary condition).

The solution of the above problem is very simple, and we can write as follows:

$\theta=\theta_1$(general solution)$+\theta_2$(particular solution)

and $\theta_2=e^{-\alpha z}\{C_0+\sum_{n=1}^{\infty}C_n\sin(n\omega t+\delta_n)\}$

where $C_0=\frac{q}{\pi k a}$, $C_1=\frac{q\alpha}{2\omega}\frac{1}{\sqrt{1+\left(\frac{k\alpha^2}{\omega}\right)^2}}$, $\tan\delta_1=\frac{\omega}{k\alpha^2}$;

$$C_n=\frac{q\alpha}{\pi n\omega}\frac{2}{n^2-1}\frac{1}{\sqrt{1+\left(\frac{k\alpha^2}{n\omega}\right)^2}},\quad \tan\delta_n=\frac{-k\alpha^2}{n\omega}$$

when n=even integer, $C_n=0$ when n=odd integer.

$\theta_1=\theta_0+\sum_{n=1}^{\infty}B_n e^{-\beta_n z}\sin(n\omega t-\beta_n z+\varepsilon_n)$ where $\beta_n=\sqrt{\frac{n\omega}{2k}}$

and the constants B_n and ε_n adequate to the given conditions can be found by the aid of the following equations

$$\begin{cases} B_1\cos\varepsilon_1=-\frac{1}{2}\frac{\alpha}{\beta_1}\left[\frac{q}{2k\alpha}+C_1(\cos\delta_1+\sin\delta_1)\right] \\ B_1\sin\varepsilon_1=\frac{1}{2}\frac{\alpha}{\beta_1}\left[\frac{q}{2k\alpha}+C_1(\cos\delta_1-\sin\delta_1)\right] \end{cases}$$

$$\begin{cases} B_n\cos\varepsilon_n=-\frac{1}{2}\frac{\alpha}{\beta_n}\left[\frac{2q}{(n^2-1)k\pi\alpha}+C_n(\sin\delta_n+\cos\delta_n)\right] \\ B_n\sin\varepsilon_n=-\frac{1}{2}\frac{\alpha}{\beta_n}\left[\frac{2q}{(n^2-1)k\pi\alpha}+C_n(\sin\delta_n-\cos\delta_n)\right] \end{cases}$$

when n is an even integer, and $B_n=0$ when the integer is odd.

3. A Numerical Example (Verification of the Theory by Observed Data)

The method of treating the actual data will be illustrated by an example. Temperature records off the coast of Shionomisaki are employed for our present purpose.[1]

(i) The annual mean temperature ($\bar{\theta}$) has the theoretical form $\bar{\theta}=\bar{\theta}_0+C_0e^{-\alpha z}$. Though the value of $\bar{\theta}_0$ can not be found directly from our data, it may be estimated at about 17.0(C°) by reference to the value of the minimum temperature at 200 m. depth. The observed temperature values at different depths give the two constants C_0 and α, and we get $C_0\fallingdotseq 6.0$(C°), $\alpha\fallingdotseq 0.5\times 10^{-4}$.

1. Taken from K. Suda's paper. Jour. Ocea. II, 491.

(ii) The amount of annual exchange of thermal quantity Q can be found from the observed data. In fact

$$Q \fallingdotseq \left[\int_0^H \sigma\rho\theta dz\right]_{Sept.} - \left[\int_0^H \sigma\rho\theta dz\right]_{Mar.}$$

where $\sigma\rho$ is the thermal capacity of water and $\sigma\rho \fallingdotseq 1$ for rough calculation. H is the depth of invariable layer, and the suffixes *Sept.* and *Mar.* indicate the respective epochs. The value of $\int_0^H \theta dz$ for autumnal and vernal equinox can be simply found by measuring the area of the isochronous curve of the temperature-depth diagram for these epochs, and, in our present case, it is estimated as $Q \fallingdotseq 1.3 \times 10^5$ (cal.)

On the other hand $Q = -\int_{\omega t=0}^{\omega t=\pi} q \sin \omega t dt$.

$$\therefore \quad q = \frac{\omega Q}{2} \fallingdotseq \frac{2 \times 10^{-7} \times 1.3 \times 10^5}{2} \fallingdotseq 1.3 \times 10^{-2}$$

(iii) From the expression $C_0 = \frac{q}{\pi k \alpha}$, we can find the numerical value of k, $k = \frac{q}{\pi \alpha C_0} \fallingdotseq \frac{1.3 \times 10^{-2}}{\pi \times 0.5 \times 10^{-5} \times 6.0} = 13.8$ (C. G. S.)

(iv) If we take the estimated values $k = 13.8$, $q = 1.3 \times 10^{-2}$, $\alpha = 0.5 \times 10^{-4}$, $\theta_0 = 17.0(C^\circ)$, as the proper constants for the ocean considered, the annual variation of temperature can be found by the present theory. The constants of the solution become

$C_0 = 6.0(C^\circ)$.			
$C_1 = 1.6(C^\circ)$.	$\delta_1 = 80^\circ 20'$	$B_1 = 4.07(C^\circ)$.	$\varepsilon_1 = 144^\circ 20'$
$C_2 = 0.34(C^\circ)$.	$\delta_2 = 355^\circ 05'$	$B_2 = 1.17(C^\circ)$.	$\varepsilon_2 = 220^\circ 00'$
$C_4 = 0.03(C^\circ)$.	.....	.....	.....
.....	.....		

Neglecting the higher harmonics, the calculated temperature approximately becomes

$$\theta \fallingdotseq 17.0 + 4.1 e^{-\beta_1 z} \sin(\omega t + 144^0 - \beta_1 z) + 1.2 e^{-\beta_2 z} \sin(2\omega t + 220^\circ - \beta_2 z) + \{6.0 + 1.6 \sin(\omega t + 80^\circ) + 0.3 \sin(2\omega t + 355^\circ)\} e^{-\alpha z}$$

where $\alpha = 0.5 \times 10^{-4}$, $\beta_1 = 0.85 \times 10^{-4}$ and $\beta_2 = 1.20 \times 10^{-4}$ and $t = 0$ at the autumnal equinox (or in September).

To compare the actual observed data with these theoretical results, both are put into the harmonic series

$$\theta = \theta_0 + a_1 \sin(\omega t + \varphi_1) + a_2 \sin(2\omega t + \varphi_2) + ...$$

The comparison of the harmonic components is listed in Table 1.

Table 1

Depth.	θ_0 (C°.)		a_1 (C°.)		φ_1		a_2 (C°.)		φ_2	
	cal.	obs.	cal.	obs.	cal.	obs.	cal.	obs.	cal.	obs.
0m	23.0	22.9	4.9	4.5	128°	107°	0.9	0.5	235°	145°
50m	21.7	22.0	3.6	3.6	107°	97°	0.4	0.3	194°	50°
100m	20.7	20.7	2.6	2.2	90°	86°	0.2	0.4	126°	321°

The coincidence for the constants of the main term a_1 and φ_1 is very good, though some discrepancies may be seen for the constants a_2 and φ_2. Remembering the bold assumption adopted in this theory, and seeing the fair agreement of the observed variations with those calculated, the writer believes that the suggested mechanisms of the variations of temperature are correct, at least qualitatively or semi-quantitatively.

4. Conclusion

(i) Applying L. F. Richardson's equation of eddy transfer of heat for mean state, the author adds, to the ordinary eddy diffusion equation, a new term of the upward flux of heat due to the spontaneous mixing occurring only in the cooling stage of water.

(ii) Though he adopts a bold assumption for the unknown terms of the upward flux of heat above mentioned, he finds comparatively good agreement between the theory and the observations.

(iii) In this paper, readers may find a physical explanation of the vertical distribution of the annual mean temperature; also a new method of finding the mean value of eddy diffusivity from the data of the vertical distribution of the annual mean temperature and the amount of annual heat-exchange of lake or ocean. He believes that his study will throw some light upon the method of reduction of the accumulated observed data of the annual variation of temperature of lake or ocean.

In conclusion the author wishes to express his hearty thanks to Dr. T. Nomitsu, Professor of Oceanography of our Geophysical Institute, for his encouragement and criticism during the study.

Proper Oscillations of the Sea of Continental Shelf[1]

By **Takaharu Nomitsu and Katakusu Habu**

(Received August 1, 1935)

Abstract

Even on the straight coast of an open sea, mareograms frequently indicate conspicuous oscillations on occasions of marine earthquakes or cyclonic storms, and the period of the oscillations is generally long, from several multiples of ten minutes up to two hours, especially a period of about one hour being the most frequent. Many investigators have taken notice of this phenomenon of which various explanations have been given. According to the writers' opinion, these oscillations are nothing but undulations of the sea of continental shelf. To confirm this view the writers measure the dimensions of the shelf seas on the charts of various parts of the Japanese coast and also of some foreign countries, and calculate the corresponding periods and show that the calculated periods agree fairly satisfactorily with the observed values.

I. Introduction

The general nature of sea-seiches, or secondary undulations in the sea, has been almost completely established by Messrs. Honda, Terada, Yoshida and Ishitani[2] and by many other investigators, and now the undulations are taken as tank-oscillations of some limited portion of sea such as a bay or an enclosed sea. Even on the *straight* coast of an *open sea*, however, mareograms frequently indicate conspicuous oscillations on occasions of marine earthquakes or of cyclonic storms, and in these oscillations we generally find a component of a long period attaining many tens of minutes to two hours, a period of about one hour being the most frequent. Since such long-period oscillations on open coasts cannot be attributed to ordinary bay-oscillations, a number of scientists have taken notice of this peculiar fact and attempted to explain it in several ways. Dr. Nagaoka[3] suggested the possible influence of an ocean current such as the Kurosiwo on the generation of long waves observed along the Pacific coast of Japan. On another occasion[4], he advanced an explanation based on the consideration of the free elastic vibration of the earth as a whole. Dr.

1. This paper was read at the Annual Meeting of the Physico-Mathematical Society of Japan on April 2, 1935. 2. Journ. Coll. Sci. Imp. Univ. Tokyo, **24**, 1 (1908).
3. Tokyo Sugaku-Buturigakkwai Kizi, **1**, 126 (1902) 4. Ditto, **4**, 35 (1907).

Terada[1] emphasized the importance of this fact in his article in "Scientific Japan Past and Present" prepared in connection with the Third Pan-Pacific Scientific Congress, 1926. In another report[2], he suggested the vibration of sial block floating on sima material as excitation of water-undulations.

Thus there seem to be two lines of opinion as to the origin of such long periods of oscillation on free coasts. One attributes it to the vibrations of the earth crust transmitting to water, and the other seeks the origin in the sea-water itself such as the influence of ocean currents. The present writers consider these oscillations to be of hydrodynamical origin and ascribe them to the proper oscillations of the so-called "shelf sea" fringing the land. Hitherto, only land and sea of horizontal configuration have been paid attention as the scene of seiche-phenomena, so that it has been difficult to understand the nature of the long period undulations found on a straight coast having no irregularities such as bays or promontories. The writers believe, however, that an abrupt change of great magnitude in the vertical depth of a sea, as well as a discontinuous change in horizontal extent, may become a cause of undulations of a proper period. On the other hand, oceanography teaches us that there exist shallow seas less than 200 m in depth, called "seas of continental shelf", making a step-like separation from the world ocean of 4000 m depth on average. Thus it is a very natural assumption that, in a shelf sea, proper oscillations may be generated by the action of a submarine earthquake or a cyclonic storm. The period for a shelf sea will of course be the same as for a bay, the line of discontinuous change in dimension always forming a nodal line in both cases.

With such ideas in mind, the writers measure the mean depths and breadths of the shelf seas along the coast of Japan and in several other regions of the world, and calculate the corresponding periods. Comparisons of the periods thus obtained with those actually observed on the mareograms constitute the present paper, and the satisfactory coincidence of the values seems to confirm our opinion. As to the generation and damping of the undulations in a shelf sea due to a cyclonic storm, one of the writers (T. N.) has touched on this problem in his paper[3] on a theory of meteorological tunamis and seiches.

1. Scientific Japan Past and Present, 284–285 (1926).
2. Report Earthq. Invest. Com. (in Japanese), **100** B, 113 (1925).
3. These Memoirs, A, **18**, 201 (1935).

2. Proper periods of the shelf seas

[A] *Japanese coast*:—In order to determine the mean depth and breadth of a shelf sea region, we draw several straight lines perpendicular to the coast at nearly equal distances from one another (Fig. 1), and measure the depths (H) along these lines using the charts[1]. With the obtained values we construct vertical sections of the sea bottom and from the sections the mean vertical section of the region.

Fig. 1

Map of Japan showing tidal station

Fig. 2 shows such mean sections for six regions of the Japanese coast.

From these sectional diagrams, we measure the breadths (L) and the mean depths ($\bar{H}$) and calculate the corresponding period (T) by the formula, $T=4\int_0^L \frac{dL}{\sqrt{g\bar{H}}}$ or $T=\frac{4L}{\sqrt{g\bar{H}}}$. No mouth-correction is needed, because the ratio of the depth to the breadth of the shelf

1. Charts used are No. 34, 53, 62, 108, 184, 144, 146 issued by the Japanese Navy.

is exceedingly small. We take the observed periods from the Journal[1] of the College of Science, Imperial University of Tokyo, Reports[2] of the Imperial Earthquake Investigation Committee, and Bulletin[3] of the Earthquake Research Institute, Tokyo Imperial University. The observed stations are shown in Fig 1. In this map the lines perpendicular to the coasts are the lines along which we measure the depths, and the dotted lines show the margin of the continental shelfs. The observed and calculated periods are compared in Table 1, and their coincidence is generally very good.

For the Sikoku Coast (Region No. 5) only, some explana-

Fig. 2

Mean sections of six shelf-sea regions

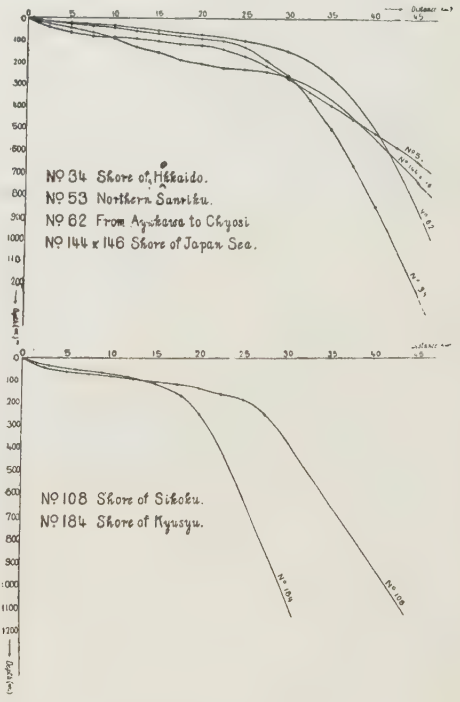

Nº 34 Shore of Hokkaido.
Nº 53 Northern Sanriku.
Nº 62 From Ayukawa to Chyosi
Nº 144 x 146 Shore of Japan Sea.
Nº 108 Shore of Sikoku.
Nº 184 Shore of Kyusyu.

Table 1. Periods along the Japanese coast

Region No.	Station No. Name	$\bar{H}$ (m)	L (km)	Period T (min.) Calc.	Obs.
1.	1. Hanasaki 2. Hamanaka 3. Kusiro	57	22.5	63	62.3 61.2~65.6 60
2.	4. Iwasaki	103	30	63	60
3.	5. Same 6. Miyako	118	30	59	75 55.2
4.	7. Niiyama 8. Ayukawa 9. Onahama 10. Minato 11. Chyosi	60 or 65	30 or 35	82 or 92	61.5, 71.6, 90 60, 77, 80 80 90 60, 66, 67, 77,
5.	12. Tei 13. Urado 14. Susaki 15. Yotu	84 (300)	25 (50)	58 (85)	49.1~52.9 51, (73.9~77.5, 80) 50~54, 61.3 (76) (75.8)
6.	16. Hososima 17. Aburatu	88	20	45	40, 43.4~49.1 37.5~39.2, 43

1. **24** (1908). 2. **34** (1909), Fig. 13, 16; **89**, 49 (1918); **100**B, 115 (1925).
3. Supplementary Vol. **1** (1934).

tion will be necessary. The period of about 50 min. at Tei and Susaki may be said to agree with the calculated period 58 min., and to represent the oscillation period of the continental shelf in this region. On the other hand, the periods of about 80 min. observed at Urado, Susaki and Yotu differ from the period calculated for the shelf sea. If we assume, however, that the whole Sikoku Coast is a great bay having its mouth line through the Cape of Asizuri and Muroto, then we get 85 min. as the proper period of this bay with mouth correction. Thus the period of 80 min. is probably the oscillation period of the great bay which consists of the entire Sikoku Coast.

[B] *Foreign coasts*:—Naturally we have not many data at hand for foreign coasts, but can give a few examples of long period oscillations at certain open straight coasts of foreign countries, observed when tunamis have propagated there from a distant epicenter. These examples are shown in Table 2, in which the periods for the shelf seas are calculated in the same way as before stated, and the observed periods are taken from the Journal[1] of the College of Science and the Bulletin[2] of the Earthquake Research Institute, Tokyo Imperial University.

Table 2. Examples of foreign coasts

Station	$\overline{H}$ (m)	L (km)	Period T (min.)	
			Calc.	Obs.
Madras	40	25	84	87
Negapatam	60	50	137	90~120
Port Elizabeth	113	60	120	140
Coast of Peru	84	30	70	
Table Bay	145	60	106	105, 100~120
Vizagapatam	90	45	101	80~120

3. Nature of the long-period oscillations on open coasts

(a) The satisfactory coincidence of the periods calculated for the shelf seas and the actual periods observed seems to show that the principal oscillations of long period are undulations of the shelf sea; and thus we believe that the origin of the period should generally

1. op. cit. 2. op. cit.

be ascribed to the sea water itself, but is not attributable to the period of vibration of the earth crust.

(b) In support of our view we bring forward the fact that the conspicuous oscillations of these periods are observed not only on occasions of submarine earthquakes but also, frequently, during storms. Fig. 3 shows examples caused by storms and Fig. 4 examples caused by earthquakes.

(c) In further support of our view, we point out the great difference between the damping of tunami caused by an earthquake and that generated by a storm. If the vibrations of the earth-crust be the direct source of the long period oscillations of water along the coast, the damping factor will be almost equal at the same place. On the contrary, if the origin is in the sea water, it is to be expected that the damping of the tunami will be smaller in an earthquake than in a storm, because, during a storm, the sea water will be far more disturbed and consequently the eddy viscosity is much greater than during a remote earthquake in calm weather.

Fig. 3

Examples of undulation caused by storms.

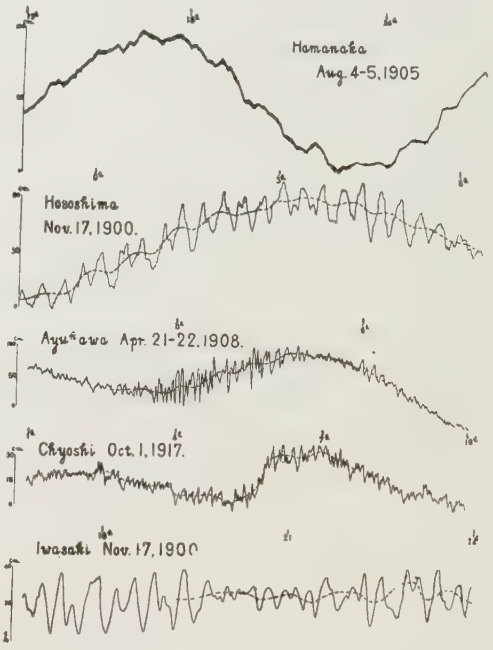
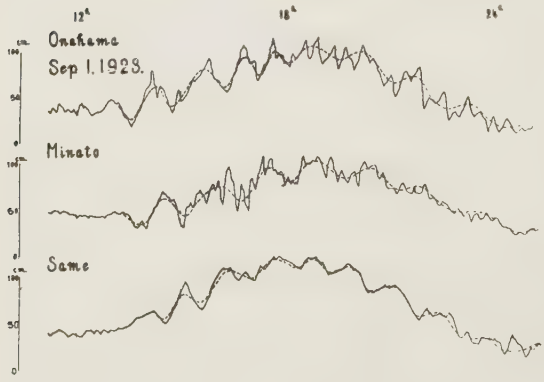


Fig. 4

Examples of undulation caused by earthquakes.

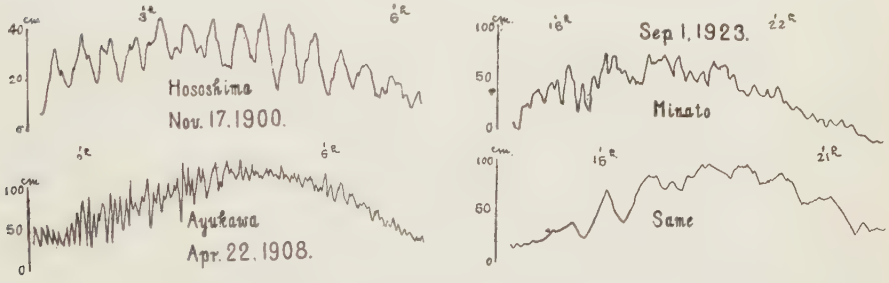


According to our theory[1] of tunami, the damping factor will be $e^{-\frac{1}{2}\nu\beta^2 t}$, where ν is the eddy viscosity, t the time and β a value such that $\beta\tan\beta H = f'/\nu$, f' being the coefficient of friction at the sea bottom. Now, Table 3 is a comparison of the actual damping factor or its index ($\frac{1}{2}\nu\beta^2$) in both cases of submarine earthquake and of cyclonic storm, and it shows evidently that the damping at the earthquake is smaller than at the storm. Several examples are shown in Fig. 5.

Table 3. Damping of the undulations

Damping in Earthquake.		Damping in Storm.	
Station	$\frac{1}{2}\nu\beta^2$	Station	$\frac{1}{2}\nu\beta^2$
Same	0.000089	Ayukawa	0.000157
Ayukawa	0.000076	Chyosi	0.000116
Onahama	0.000041	Hososima	0.000141
Minato	0.000041		
Chyosi	0.000065		
Urado	0.000058		
Hososima	0.000048		
Madras	0.000048		
Negapatam	0.000051		

Fig. 5 Comparison of damping of oscillations in storm and in submarine earthquake



(d) Another subsidiary support is that, as seen before, the period of oscillation is not necessarily the same everywhere, but differs according to the locality of the coast, even for tunamis caused by one and the same earthquake and propagated from a very distant epicenter.

The authors wish to express their hearty thanks to the Hattori Hôkôkwai for the grant given for the present research.

1. These Memoirs, A, **18**, 201 (1935).

Volcanic Micro-Tremors and Eruption-Earthquakes[1]

(Part I of the Geophysical Studies on the Volcano Aso)

By **Kenzô Sassa**

(Received August 5, 1935)

1. Introduction

During an explosively active time of volcanoes, micro-tremors of volcanic origin are generally observed, and have been described by various authorities for Usu-san,[2] Asama-yama,[3] Mihara-yama,[4] Taal,[5] Vesuvius,[6] Mauna Loa,[7] Kilauea,[8] etc., but neither the nature of the volcanic micro-tremors nor their modes of occurrence have not been investigated by these writers. As to the volcanic earthquakes directly accompanying eruptions, which will be called eruption-earthquakes in the present paper, Omori[9] simply mentions that the initial motion is sometimes directed towards, and at other times outwards from, the crater, giving no further information about the nature and the mechanism of occurrence of eruption-earthquakes. The present investigations and considerations based on the micro-seismometrical observations made at the Volcano Aso were undertaken to throw some light upon the above points, which will be discussed in the following pages.

2. Observing stations

Our Volcanological Laboratory, 7.3km to the west of the crater, was the central station. There are two mountain stations connected with the laboratory, one at Kusasenrigahama, about midway between the crater and the laboratory and the other at Hondô near the crater. Besides these, four temporary stations were established, one at the Miyadi Girls' High School, 7.3km NNE of the crater, and the three others at Suzuriisi, Sara-yama, and Taka-dake, around the crater. The

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1. An abstract of this paper was read at the Annual Meeting of the Mathematico-Physical Society of Japan, Tokyo, 1934 April.
2. F. Omori: Bull. Imp. Eqke. Invest. Comm. 5 (1911). 3. F. Omori: Ditto. 7 (1914).
4. F. Omori: Shinsai Yobo Chosakwai Hokoku 81 (1915).
5. M. S. Maso: The eruption of Taal volcano January 30, 1911.
6. F. Signore: Publ. Bureau Cent. Seism. Intern. 7 (1932).
7. T. A. Jaggar: Bull. Seis. Soc. Amer. 10 (1920).
8. Ditto. 9. F. Omori: Loc. cit.

positions of the stations, 7 in all, will be seen in the following Table 1 and Fig. 1.

Table 1

Station	Azimuth from the crater	Distance from the crater	Height above sea-level
The Laboratory	W	7.3km	568m
Kusasenrigahama	W	3.1	1100
Hondô	WSW	1.0	1170
Miyadi	NNE	7.3	530
Suzuriisi	NNW	1.0	1190
Sara-yama	SSE	1.0	1250
Taka-dake	E	1.9	1520

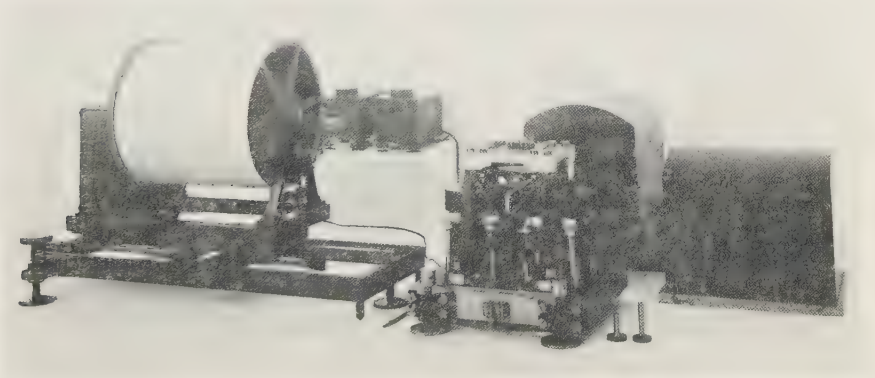
Fig. 1. Map of a part of the Volcano Aso showing the positions of the observing stations.

3. Instruments

At the central station, the Volcanological Laboratory, Wiechert horizontal component seismograph of 1000 kgs weight and vetical one of 1300kgs weight have been installed on concrete bases 2 m. square and 2m. deep, insulated from the floor in the underground rooms and have been continuously at work since May 1929. The magnification for the horizontal component was kept at 200 for short period vibrations and that of the vertical one at 150. When the volcano was in violent activity, the amplitude of the micro-tremors recorded reached 3mm on smoked paper even at a distance of ca. 7.3km from the crater, and it was not necessary to raise the magnification of the instrument above this degree. But when the volcano is in repose, the amplitude of micro-tremors does not exceed a fraction of a micron, and therefore the following two types of electromagnetic

system were prepared for the present investigation. The instruments of the first type, short period horizontal micro-seismographs of very high magnification (ca. 20,000 maximum), were essentially the same as that which was constructed in 1925, in our Geophysical Institute at Kyoto according to Prof. Shida's design, and successfully recorded more than ten thousands aftershocks of the Tadima Earthquake of 1925 during the period of the year following the main shock. But, since the stationary mass of the latter instrument was too great to be aperiodic, I reduced its weight to 1.8kgs, and interchanged the positions of the coils and the damper plate, putting the latter further than the former from the vibration axis. The period of the pendulum increased slightly (0.55 second) in consequence, which was rather to be preferred for our present works at Aso. Fig. 2 shows the horizontal

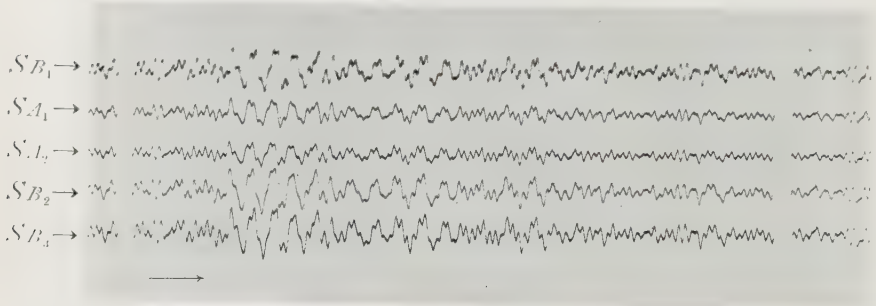
Fig. 2. Short Period Micro-seismographs, S_R, with Galvanometers and Recording Cylinder.



component micro-seismographs with galvanometers and recording drum. The general dimensions of the different parts of the instrument can be estimated from the dimensions of the recording drum which is about 30 cm. both in length and in diameter. The massive base is of bronze, supported on three strong levelling screws. Bolted to this is a rigid bronze frame-work which carries the pendulum. The pendulum is a simple vertical pendulum of a stationary mass of 1.8kg. to which are rigidly keyed the coils and copper plate. The axis of rotation is neatly arranged to avoid friction by using crossed ~~Cardan~~ springs screwed to the fixed framing and to the pendulum. The damping magnets and the magnets for the coils are mounted on the base and pairs of magnets are provided with screw adjustments so that the

damping and magnification may be controlled to the desired extent. The galvanometer is of Moll's moving coil type. The coil of an area of $0.2 \times 3\ cm^2$., moving in a strong magnetic field of ca. 2000 Gausses, is stretched between two fine strips. Two instruments of this type of short period micro-seismographs, S_A, were made in the spring of 1930 and set up in the underground room of the Laboratory. After the completion, in the summer of 1931, of three other sets of the same type of instrument, S_B, the comparison of these five sets of short period micro-seismographs was carried out by setting their pendulum parts on a single concrete base and facing in the same direction, and registering the movements of their galvanometer mirrors on a single recording drum. As shown in Fig. 3, the five recorded curves corresponding to the five sets of micro-seismographs are quite satisfactory,

Fig. 3. A portion of the record of comparison of the five sets of the short period micro-seismographs. (Time between two consecutive marks=30 sec.)

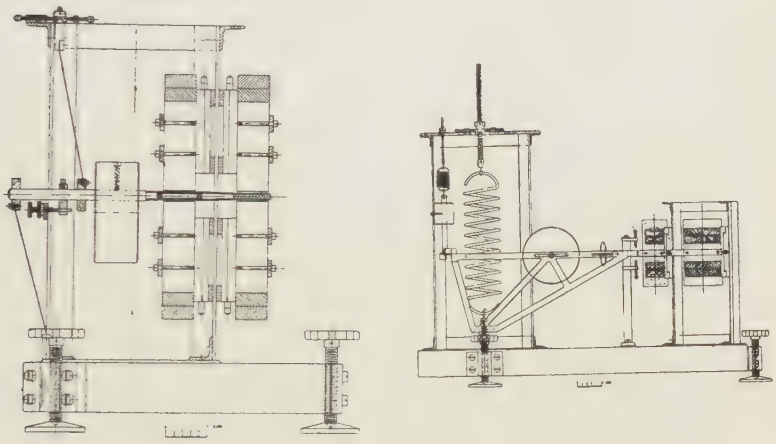


(1/2×the original record)

being almost similar, even in detail. To see the effect on micro-tremors of a superficial layer of ashes on the ground and of the laboratory building, two components of S_B were set in December 1931 directly on volcanic rock in a pit of ca. 20 m. depth at a distance of ca. 60 m. NNE of the building. The lead-wires of ca. 90 m. length from the pendulums to the galvanometers, were inserted into iron-pipes burried in the ground at a depth of ca. 1 m., and, after careful observation, it was confirmed that no disturbances were introduced by the long lead-wires. As to the effect of surface layers and the building the readers will find some accounts in the subsequent articles. The second type of micro-seismograph is the Galitzin system of medium period. The pendulum parts of the set G_A of two horizontal components and one vertical component, were originally made by the Cambridge Instrument Co., but their galvanometers of Moll's moving coil type were con-

structed by the author to increase their magnification for shorter periods. The galvanometer coil was stretched between two fine phosphor bronze wires of 15 microns dia., taking the utmost care not to let its center of gravity fall outside the axis of rotation. Another set of the same type of instruments, G_B, consisting of two horizontal components and one vertical component, were made by the present writer in March 1933. Their construction is essentially similar to G_A, but their dimensions and weights were greatly reduced to make the instruments more portable, without changing their magnification. Fig. 4 (a) and (b) are sketches of the pendulum parts of the micro-seismographs G_B. In

Fig. 4. Pendulum parts of the microseismometer G_B.



(a) Horizontal component (b) Vertical component

order to give a longer period of free oscillation to the pendulum, in spite of the reduced dimensions of the instrument, the pendulum part of the vertical component seismograph, as shown in Fig. 4(b), has a second spring besides the main spiral spring suspending the pendulum. The instrumental constants of the seismographs are summarized in the following Table and their magnification curves are shown in Fig. 5.

Table 2

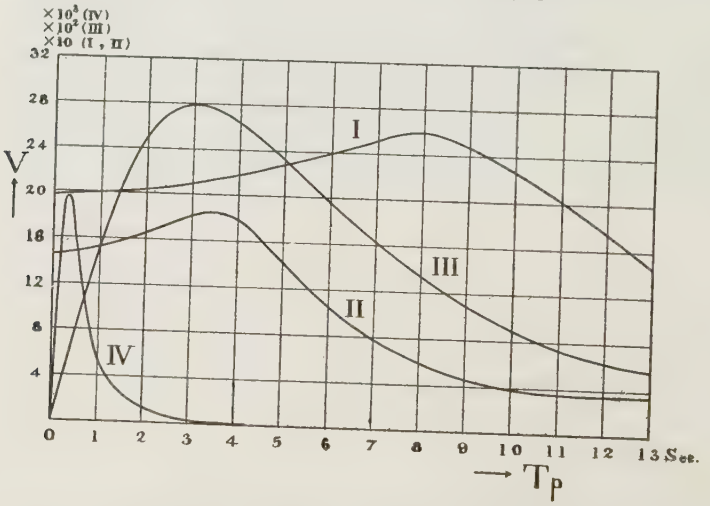
Instrument	T_0 sec.	μ^2_0	V	T_1 sec.	μ^2_1	k	l cm.	V_m	s cm.
Wiechert seismograph horizontal comp.	10.0	0.81	200						3
Wiechert seismograph vertical comp.	4.6	0.81	150						3
Micro-seismograph, S_A	0.55	0		0.55	0	16100	7.5	12300	30

Table 2 (Continued)

Instrument	T_0 sec.	μ^2_0	V	T_1 sec.	μ^2_1	k	l cm.	V_m	s cm.
Micro-seismograph, S_B	0.55	0		0.55	0	25600	7.5	19300	30
Micro-seismograph, G_A horizontal comp.	8.0	0		4.0	0	627	12	2800	3
Micro-seismograph, G_A vertical comp.	8.0	0		4.0	0	1975	38	2800	3
Micro-seismograph, G_B horizontal comp.	8.0	0		4.0	0	340	6.5	2800	3
Micro-seismograph, G_B vertical comp.	8.0	0		4.0	0	1410	27	2800	3

T_0: Period of free oscillation of the pendulum. μ^2_0: Damping constant of the pendulum, $\mu^2_0 = 1-(\epsilon_0/n_0)^2$. V: Magnification of the seismograph for short period vibrations. μ^2_1: Damping constant of the galvanometer, $\mu^2_1 = 1-(\epsilon_1/n_1)^2$. k: Uebertragungsfaktor of the seismograph. l: Length of the equivalent simple pendulum. V_m: Maximum magnification of the micro-seismograph. s: Speed of the recording paper per minute.

Fig. 5. Magnification curves of the seismographs. I: Wiechert horizontal comp. seismograph. II: Wiechert vertical comp. seismograph. III: Micro-seismographs, G_A and G_B. IV: Micro-seismographs, S_B.



4. Ordinary micro-tremors of non-volcanic origins.

Our sensitive micro-seismographs are never at rest, showing that there are always small movements of the earth's crust which are called micro-tremors. Micro-tremors of a period of about 0.3 seconds, caused by traffic, industry, wind, waterfalls, rain and probably some other causes, are incessantly recorded by our short period micro-seismographs,

$S_{A,B}$ at each of our observatories. The micro-tremors of this nature observed at our Geophysical Institute of Kyoto which is situated at the NE corner of the city, are about 1 micron in double amplitudes in the daytime and only ca. 0.3 micron at night, the period being 0.35 seconds. While at our Kamigamo Geophysical Observatory which is almost perfectly free from mechanical disturbances, being isolated on a hill at a distance of ca. 4.5 km. NNW of the University, the micro-tremors recorded were only ca. 0.1μ even in the daytime and ca. 0.03μ at night, the period being ca. 0.33 sec.. Micro-tremors of the same period of ca. 0.33 sec. and of constant amplitude of ca. 0.03μ both in the daytime and at night are observed at our Abuyama Seismological Laboratory, which is almost free from mechanical disturbances, being isolated at a distance of ca. 4 km. from the nearest railway and small town. The amplitude of the micro-tremors observed at our Aso Volcanological Laboratory was ca. 0.1μ in the underground room on calm days, while it was only ca. 0.02μ when observed directly on volcanic rock in the pit of ca. 20 m. depth. As to the micro-tremors observed on windy days, and to the effect of surface layers and the building the readers will find some account of these in a paper written by Mr. E. Nishimura.[1] Micro-tremors of ca. 0.5 sec. period caused mainly by water-falls were frequently recorded at our Volcanological Laboratory and will be described in Appendix of the present paper. The period of the micro-tremors observed at our mountain station of Kusasenrigahama was 0.35 sec., the amplitude being ca. 0.1μ, while that observed at our summit station of Hondô was only 0.22 sec.. The amplitude observed at the latter observing room standing on ground of lapilli of ca. 10 m. depth was almost always ca. 0.1μ, while that observed at Jabara, where the pendulum was set directly on volcanic rock, was only ca. 0.05μ. The micro-tremors above described, except those caused by strong wind and heavy rainfalls, are considered as proper oscillations of the ground of the observatories. Ordinary microseisms of periods ranging from 4 to 12 sec. recorded at our Volcanological Laboratory were less than 0.5μ in double amplitudes in a quiet season, and so they did not normally interfere with the volcanic micro-tremors of the second kind, the period of which is nearly the same.

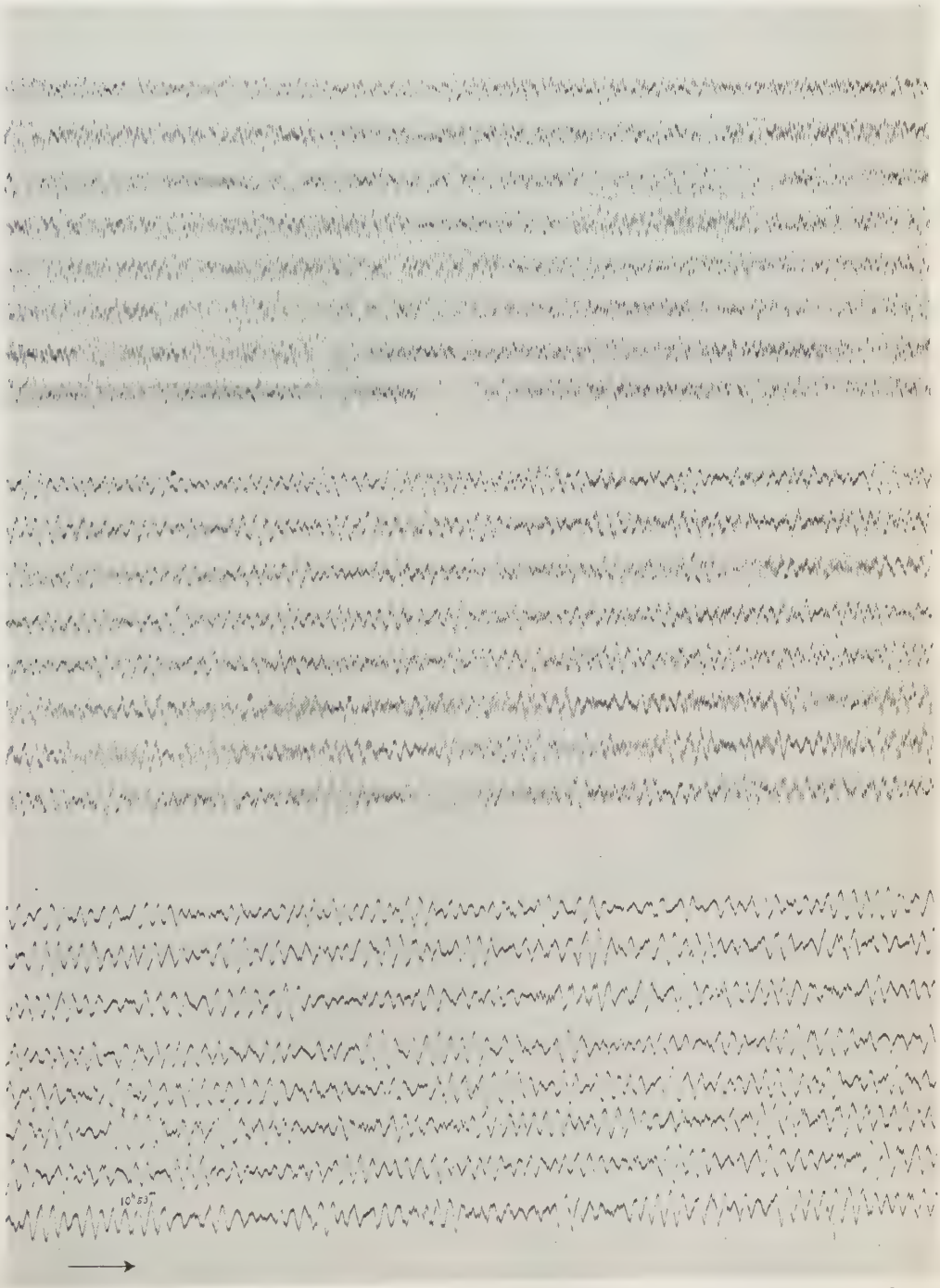
5. The volcanic micro-tremors of the first kind

There are four kinds of micro-tremors of volcanic nature observed at the Aso Volcanological Laboratory. When the new laboratory was

1. E. Nishimura's paper will appear in these Memoirs in near future.

finished and the Wiechert instruments were set up in May 1929, the Volcano Aso was still in activity, the first explosion having taken place on April 1,1927, and the micro-tremors of the first kind with a period ranging from 0.8 to 1.5 sec. were almost continuously recorded till the end of the year. But when the high magnification instruments were introduced next year, it was found that the micro-tremors of this kind did not cease to exist even in quiescent periods of the volcanic activity. They occurred not in continuous trains, but intermittently, several groups per hour, each of which consisted of 5–10 somewhat regular waves of 1μ or less in double amplitudes. Fig. 6 in Plate I is a reproduction of the record of the micro-tremors of this kind registered by short period micro-seismographs, S_B on Nov. 28, 1931. As will be seen from the record the beginning of the group of waves is not clearly defined. When the volcano becomes active the wave-group of the micro-tremors of the first kind increases gradually in frequency and amplitude in parallel, and finally becomes a continuous train of irregular waves as shown in Fig. 7, which is a reproduction of a portion of a record registered by the micro-seismographs G_A, on Feb. 25, 1933. At that time the maximum magnification of the instruments was reduced to about 200, for the occasion was the day on which the great explosive eruptions of the First and the Second crater occurred frequently, and the amplitudes of the micro-tremors of the day were the greatest ever observed at our Aso Volcanological Laboratory. It will be noticed that the micro-tremors of the first kind are predominant in the N–S component, while those of longer period of the second kind are more predominant in the E–W and vertical components which will be described in the next article. The oscillatory displacements of the micro-tremors of the first kind are practically confined to the horizontal plane, and approximately to the N10°W–S10°E direction, which is roughly at right angles with respect to the direction of the crater. The amplitude of the tremors of this kind recorded by the seismographs set directly on volcanic rock in the pit of ca. 20 m. depth is reduced to 0.85 of the corresponding amplitude observed at the underground room of the laboratory. During an active period of the volcano, the amplitude at Hondô of the volcanic micro-tremors of the third kind, the period of which is ca. 0.5 sec. is far larger than that of the first kind, so that it is very difficult to study the nature of the latter tremors in detail. But in times of repose the former is vanishingly small in amplitude, while the latter still remains considerable in amplitude. The period of the micro-tremors of the

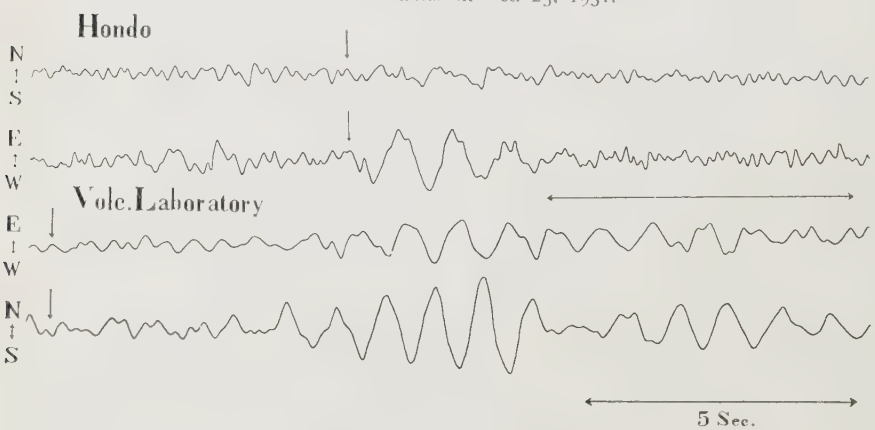
Fig. 7. A portion of the record obtained from the micro-seismographs, G_A, at the Volcanological Laboratory on Feb. 25, 1933. At that time the maximum magnification of the instruments was reduced to about 200 and the amplitudes of the micro-tremors of the day were the greatest ever observed at the laboratory. (Time between two consecutive marks = 1 min.)



(2/3 × the original record)

first kind observed at Hondô ranges from 0.7 to 1.0 sec. and the displacement is wholly horizontal, or at least the vertical component is less than one twentieth of the former. The orbit of each element is elliptic, being clockwise in sence, and its major axis lies approximately in the direction N74°E-S74°W, the ratio of the major axis to the minor being ca. 3 : 1. The Hondô observing room which is of concrete and half underground, stands on a ground of lapilli of about 10 m. depth. To test the effect, if any, of the surface layer and the observing room, one of the pendulums was set in the room and the other one directly on volcanic rock at Jabara at a distance of 150 m. north of the former, but no differences of phase or amplitude were found between the two records. During a time of long repose, a group of micro-tremors of the first kind consists of 3 or 4 waves at the summit station of Hondô, while at the foot station of the Laboratory the number of waves of the corresponding group increases to 5 or 6 in general. By a series of simultaneous observations taken at the two stations from Sept. to Nov. 1931, it was found that the amplitude at the foot station was slightly reduced, being 0.92 that of the summit, while the period at the former was 1.2 times that at the latter. The time of occurrence at the Laboratory was delayed 6.4 sec. as compared with that at Hondô. The identification of the corresponding phases of the micro-

Fig. 8. Comparison of the records of simultaneous observation at the two stations on Oct. 25, 1931.



tremors observed at the two stations was easily made as shown in Fig. 8, in which the arrows indicate the same moment in the records at the two stations. Some results of these simultaneous observations are given in the following table :

Table 3

Date	Time of occurrence	At Hondô			At the Laboratory			Time diff.
		A_N	A_E	T	A_N	A_E	T	
1931	h m s	μ	μ	sec.	μ	μ	sec.	sec.
Oct. 6	21 43 06	0.22	1.14	0.83	0.77	0.53	0.98	6.50
16	21 39 45	0.22	0.78	0.77	0.53	0.18	1.05	6.00
16	21 40 26	0.19	0.64	0.89	0.50	0.18	1.05	6.60
20	21 39 17	0.69	0.97	0.76	1.17	0.55	1.12	6.30
25	21 41 03	0.56	1.70	0.93	1.33	0.67	0.93	6.46
29	21 37 02	0.33	0.97		0.58	0.33		6.24
29	21 40 49	0.42	1.10	1.10	1.00	0.55	1.13	6.25
Nov. 11	21 39 49	0.33	0.56		0.35	0.20	1.03	6.70
11	21 42 53	0.70	1.00	0.80	0.83	0.37	0.83	6.70
	Mean	0.37	0.89	0.87	0.79	0.40	1.03	6.42
		μ 0.96			μ 0.89			
	Ratio	0.96/0.89=1.08						

At the beginning of the great explosive activity of Oct. 1932, simultaneous observations were again taken at the summit and the foot stations. In this case the ratio of the amplitude at Hondô to that at the Laboratory was 2.4 instead of 1.1 in the preceding quiescent year of the volcano, while the time difference of occurrences was 5.2 sec. instead of 6.4 sec. This difference is very interesting and will

Table 4

Date	Time of occurrence	At Hondô			At the Laboratory			Time Diff.
		A_N	A_E	T	A_N	A_E	T	
1932	h m s	μ	μ	sec.	μ	μ	sec.	sec.
Oct. 21	18 44 48	0.28	0.70	0.90	0.35	0.17	1.00	5.20
	18 53 55	0.25	0.92	0.76	0.42	0.22	1.00	5.15
	18 58 12	0.25	0.97	0.90	0.35	0.18	1.00	5.60
	19 46 08	0.28	1.11	1.00	0.33	0.13	1.00	5.40
	21 24 34	0.47	1.39	0.98	0.50	0.25	0.87	5.03
	22 21 39	0.56	1.39	0.82	0.50	0.20	0.98	5.10
	22 33 08	0.58	1.39	0.83	0.50	0.23	0.90	5.15
22	10 36 51	0.97	2.50	0.81	0.88	0.37	0.80	5.10
	Mean	0.45	1.30	0.88	0.48	0.22	0.95	5.22
		μ 1.38			μ 0.58			
	Ratio	1.38/0.58=2.38						

be considered in another place in this paper. Some results of the observations are given in Table 4.

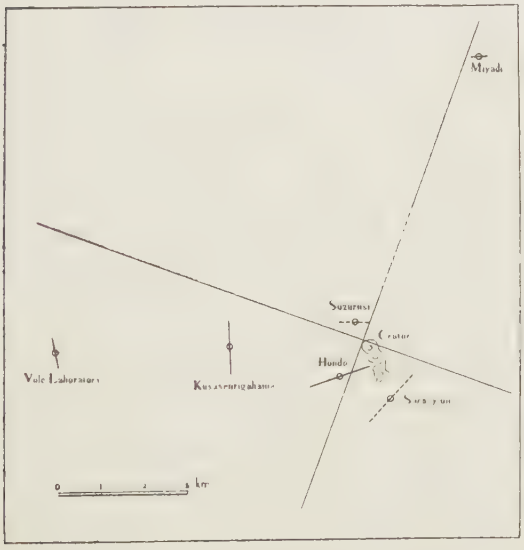
For further study of the nature of the tremors the micro-seismographs, S_A were installed in the Girls' High School at Miyadi, which station is at nearly the same horizontal distance from the crater, as is the Volcanological Laboratory, while their directions are roughly at right angles with respect to the crater. The displacement of the micro-tremors of the first kind in Miyadi consists of elliptic oscillations, whose major axis is nearly in the E–W direction, the ratio of the major axis to the minor being about 3 : 1. The simultaneous observations at Miyadi and the Volcanological Laboratory show that the times of occurrence were nearly concurrent and the ratio of the amplitude at Miyadi to that of the laboratory was about 0.6 : 1. This latter result is rather contrary to expectation, seeing that the superficial layer of volcanic ashes at Miyadi is about 90 m. depth or more, and thicker than that at our laboratory. On Oct. 23–24, 1932 a set of two micro-seismographs, Type S_A was set directly on volcanic rock in a pit of ca. 10 m. depth at Kusasenrigahama, which lies in the line connecting the crater with the Laboratory as shown in Fig. 1. The period and the mode of oscillations of the micro-tremors of the first kind at the two stations were quite similar, but the amplitude at the former was twice that at the latter. On Aug. 24, 1933 the two components of the micro-seismographs, Type S_A were set in a tea-house which stands almost directly on the lava bed at Suzuriisi and is at a distance of ca. 500 m. NNW from the First Crater, the most northern of the four active craters. The amplitude of the micro-tremors observed at this station is exceedingly small as compared with that at Hondô and the displacement of the earth element describes an elliptic orbit, its major axis lying in the E–W direction and the ratio of the major axis to the minor being 3 : 1. On Aug. 29, 1933 micro-tremors of the same kind were registered by the same set of seismographs on a concrete base of 1.0×1.5 m^2. of 1.5 m. depth, which was constructed on a ground of volcanic fragments and ashes of about 10 m. depth at Sara-yama at a horizontal distance of 1.5 km. SES from the First Crater. The amplitude of the micro-tremors of the third kind was so great that the tremors of the first kind were almost perfectly masked, but from a close examination of the records, the major axis of the oscillating ellipse of the latter seems to be approximately in the direction $N45°E$-$S45°W$, the ratio of major to minor

axis being 2 : 1. The results of the observations at the 6 stations described above, are tabulated in Table 5, in which Δ is the horizontal distance of each station from the First Crater and α the ratio of the amplitude at the Laboratory to that at the corresponding station, the former reduced to the surface value, for the observations were made in the pit and the amplitudes were reduced to 0.85 of the surface values.

Table 5

Station	Δ	$\alpha_{obs.}$	$\alpha_{calc.}$	$\gamma_{obs.}$	$\gamma_{calc.}$	φ
	km					
The Laboratory	7.30	1	1	80°	90°	65°
Miyadi	7.25	0.5	0.1	64	45	1.5
Kusasenrigahama	3.10	1.7	1.4	90	90	65
Hondô	1.10	2.0	2.0	38	40	14
Suzuriisi	0.50			68	88	32
Sara-yama	1.30			60	79	44

Fig. 9. Directions of the major axes and amplitude ratios of the micro-tremors of the first kind.



From the results of observation above described it is concluded that the volcanic micro-tremors of the first kind are a kind of generalized Love waves, having a certain azimuthal distribution of displacement as demonstrated by H. Nakano[1] and K. Sezawa.[2] According to H. Nakano, the equation of the path of the element of the medium is given by $x = D_\omega R_2 \cos(pt - \theta_2)$, $y = D_\varphi R_1 \cos(pt - \theta_1)$, where the X-axis is along the radius vector passing the position at rest of the element, its positive sense coinciding with the increasing sense of ω, and the Y-axis, perpendicular to it, has the same positive sense as

1. H. Nakano; Geophy. Mag. **2** (1929).
2. K. Sezawa; Bull. Earthq. Res. Inst., **7** (1929).

the increasing sense of φ, and $D_\omega = 2Sn\cos\beta z\cos n\varphi\frac{1}{k\omega}$

$D_\varphi = -S\cos\beta z\sin n\varphi$

$R_1 = 1/\sqrt{\{J_{n-1}(k\omega)-J_{n+1}(k\omega)\}^2+\{Y_{n-1}(k\omega)-Y_{n+1}(k\omega)\}^2}$

$R_2 = 1/\sqrt{J_n^2(k\omega)+Y_n^2(k\omega)}$ $\theta_1 = \cos^{-1}\frac{J_{n-1}(k\omega)-J_{n+1}(k\omega)}{R_1}$

$\theta_2 = \cos^{-1}\frac{J_n(k\omega)}{R_2}$. The angle γ between the major axis and X-axis is given by $\tan 2\gamma = \frac{2\varepsilon\cos(\theta_2-\theta_1)}{\varepsilon^2-1}$, $\varepsilon = \frac{D_\omega R_2}{D_\varphi R_1}$,

the sign of $\cos 2\gamma$ being the same as that of ε^2-1. Taking the position of the origin of the disturbance at the north wall of the First Crater as shown in Fig. 9, the amplitude and the angle γ corresponding to the distance of our observing stations were calculated by the above solution, taking $n=2$. If two azimuths of purely radial motion are taken as drawn in Fig. 9, the calculated amplitude ratios $a_{\text{calc.}}$ and angles $\gamma_{\text{calc.}}$ are in fairly good coincidence with those of the observed values as given in Table 5. Since the oscillatory movements of the micro-tremors might be considered as being greatly disturbed by the irregular formations of the upper crust of the volcanic district and since, moreover, our observations at temporary stations cover only a few days, no conclusive discussions about the discrepancies between the calculated and the observed values can be admitted. As already described, the amplitude observed at Miyadi is to be considered as being increased by the deep surface layer of volcanic ashes at the station. As to the mode of oscillations at the internal source of disturbances as well as the mechanism of the volcanic eruptions to be inferred from the observed data, some considerations will be given in a subsequent article of the present paper. The case observed in the repose time of 1931 can not be explained by the above calculation, but in this case we have to take $n=1$ instead $n=2$ in the above calculation. If the azimuth of purely radial motion is considered as coinciding with the line, connecting Miyadi and Hondô as shown in Fig. 9, and the origin of the disturbance is directly under the First Crater, then the calculated amplitudes corresponding to the distances, and the azimuths of the Laboratory and of Hondô become as follows :

	Amplitude observed	Amplitude calc.	Azimuth
The Laboratory	1	1	65°
Hondô	1.1	1.1	15°

The calculated values are in good coincidence with those obtained by observation. The time difference of occurrence observed in Oct. 1931 between the summit and the foot stations was 6.4 sec., while in Oct. 1932 it was reduced to 5.2 sec.. If this change in time could be considered as occurring simply from the change in depth of the origin of disturbance, deeper in the active time of 1932 than in the repose time of the preceding year, then the velocity of propagation of the micro-tremors of the first kind is 0.99 km./sec., taking the origin of disturbance as just below the bottom of the First Crater.

6. The volcanic micro-tremors of the second kind

The volcanic micro-tremors which the writer calls the "second kind" are recorded in repose as well as in active times of the volcano, and the oscillatory movements are very smooth and regular and of periods ranging from 3.5 sec. to over 8 sec.. The period persists so long as the state of activity of the volcano does not change. The horizontal movement observed at the Volcanological Laboratory is practically confined to the direction of the crater and the vertical motion is as pronounced as the horizontal, the phase being upward corresponding to the westward motion. In a repose period in the summer of 1932, or, strictly speaking, in the time of preparation for next explosive eruptions, the micro-seismographs, Type G_A at the Volcanological Laboratory recorded several groups of micro-tremors of the second kind per hour, each group consisting of 3–6 regular waves of about 2μ in double amplitudes. Fig. 10, Plate I is a reproduction of the record obtained at the Laboratory on July 27, 1932. As shown in the record the micro-tremors of the second kind predominate in the E–W and vertical components, while in the N–S component those of the first kind predominate. When an explosive eruption approaches, the recorded group of waves of the micro-tremors gradually increases in frequency and finally becomes a continuous train of regular waves, the amplitudes of which also increase at the same time. Fig. 9 is a typical record obtained during the explosively active time of the volcano already described. At the Hondô observing room, observations were made twice with the micro-seismographs, G_A, once in Oct. 1932 and again in Aug. 1933. The horizontal motion of the micro-tremors of the second kind observed here was practically confined to the direction N74°E–S74°W which is the direction towards the centre of the four craters. In the right-angled direction the displace-

ments were smaller than one-fifth of the former component while the periods were about half those of the former. The vertical component was recorded on all occasions with the same value as the horizontal, the phase being upward corresponding to a S74°W-ward motion in the horizontal plane. In Oct. 1932, when the last great explosive activity of the volcano began, the micro-tremors of the second kind were recorded about 10 groups per hour, each of which consisted of 5–7 waves of a few microns in double amplitudes. In the following figure 11 the amplitudes and the periods of the micro-tremors observed at Hondô during Oct. 21–26, 1932 are plotted but show no definite relation to one another. But Fig. 12 seems to show that the ratio of the recorded horizontal amplitude to the vertical increases as the period decreases.

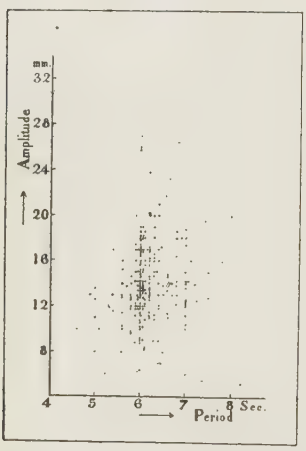


Fig. 11. Amplitudes and periods of the micro-tremors of the second kind at Hondô.

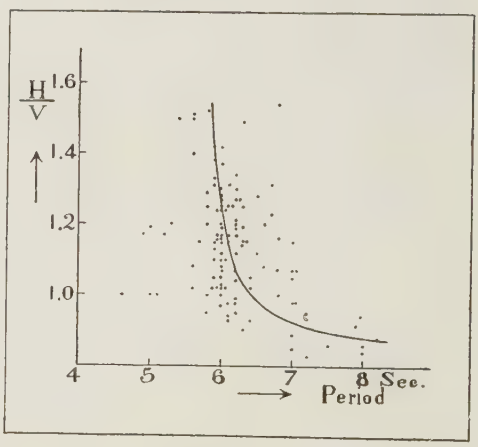


Fig. 12. Ratio, H/V, of the horizontal amplitude to the vertical and period of the micro-tremors.

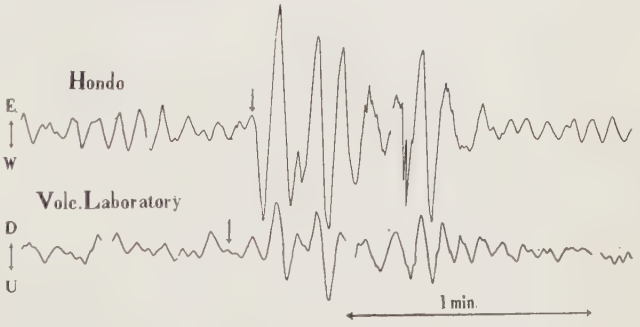
Fig. 13 is a reproduction of a portion of the record registered by the micro-seismographs, Type G_A, on Oct. 23, 1932 at Hondô. The wave group of the micro-tremors of the second kind consists generally of two parts, the preliminary part of irregular waves of smaller amplitude and the regular waves of the principal part of larger amplitude. The duration of the preliminary part ranges from 10 sec. to over 30 sec., having no definite connection with the apparent emergent angles and the periods of the waves. The micro-tremors of the second kind were frequently observed to be accompanied by those of the first kind, which latter were recorded from 0 to 20 seconds before the recorded

Fig. 13. A portion of the record obtained from our G_A type micro-seismographs on Oct. 23, 1932 at Hondô. Large wave groups in the E-W and the vertical component are the micro-tremors of the second kind. E′=E16°N, N′=N16°W (Time between two consecutive marks = 1 min.)

(3/5×the original record)

initial phase of the principal part of the former, but sometimes they were observed independently of each other. This diversity of mode of occurrences is very interesting when we consider the origins of the disturbances. According to the simultaneous observations taken at Hondô on the summit and at the Laboratory at the foot, the modes of oscillatory motion of the micro-tremors of the second kind recorded were quite similar both in their periods and phases, but the amplitudes observed at the foot station were about 0.4 of those

Fig. 14. Comparison of records simultaneously registered at the two stations, the arrows indicating a simultaneous moment in the two records.



at the summit station as shown in Fig. 14. Table 6 contains some results obtained from simultaneous observations of the micro-tremors of the second kind at the summit and the foot stations.

Table 6

Date		Hondô		The Laboratory		Ampl. Ratio A_E/A_V	Time Diff.
		A_E	T	A_V	T		
	h m	mm.	sec.	mm.	sec.		sec.
Oct. 26	21 47	12.6	6.2	7.0	6.2	1.80	7.6
	23 12	11.0	6.0	6.0	5.9	1.83	6.2
	39	9.1	6.0	3.7	6.2	2.46	6.4
	54	10.5	6.2	5.2	6.0	2.02	6.4
27	6 47	14.0	5.7	5.5	5.0	2.54	6.8
	7 07	11.0	6.4	6.4	6.0	1.72	7.4
	8 26	12.5	6.0	5.0	5.3	2.50	7.5
	11 04	27.0	6.0	10.0	6.1	2.70	5.8
	58	21.0	6.3	6.5	6.2	3.24	8.0
	12 43	22.0	6.0	7.4	5.2	2.97	8.0
	44	22.5	6.2	7.5	6.0	3.00	7.0
	13 39	30.0	6.0	11.5	6.2	2.61	6.8
	14 16	18.0	7.0	5.2	6.0	3.46	7.6
	40	18.0	6.0	6.7	6.0	2.69	7.0
	16 22	16.0	5.9	5.6	6.2	2.86	7.6
	26	19.5	6.2	6.4	6.1	3.04	6.8
	17 15	32.0	5.6	12.6	5.8	2.54	8.0
	18 14	19.0	6.6	7.1	6.4	2.67	7.6
	26	16.5	6.2	8.0	6.2	2.06	7.0
	30	12.5	6.0	7.4	6.0	1.69	6.7
	55	14.0	6.0	8.0	5.7	1.75	6.8
	20 10	17.5	6.0	5.2	5.9	3.36	7.0
	21 28	24.0	6.0	10.0	6.0	2.40	6.0
	Mean	17.82	6.11	7.12	5.94	2.50	7.05

The time of occurrence of the micro-tremors observed at the foot station was delayed about 7 seconds as compared with that at the summit station. The velocity of propagation of the micro-tremors of the second kind determined from the observed time difference of occurrences is 0.90 km./sec. which is to be taken as the velocity of Rayleigh waves in the district. As will be explained in the next paragraph, the micro-tremors of the second kind seem to be a kind of Rayleigh wave, but not the ordinary one, for the horizontal longitudinal vibrations virtually coincide in phase with the vertical, which

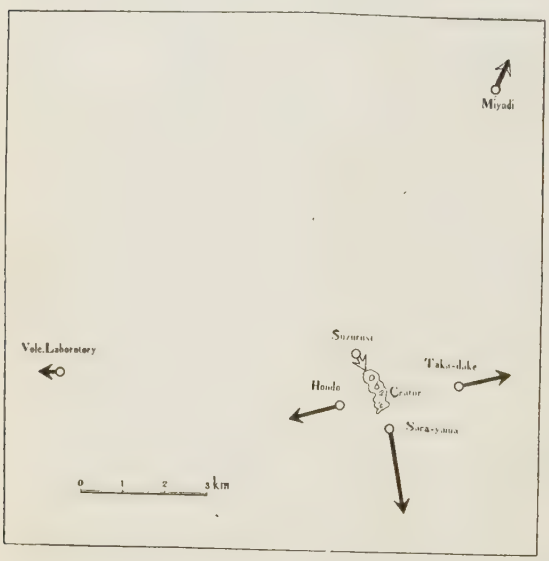
is not in accord with the theory of ordinary Rayleigh waves. On Oct. 29, 1932 two horizontal component micro-seismographs, G_A were set up at the Girls' High School at Miyadi, where, the amplitude of the ordinary pulsatory oscillations being very large, the recorded micro-tremors of the second kind were greatly disturbed. The horizontal displacements of the micro-tremors here observed were practically confined to the direction of the crater. The simultaneous observations at Miyadi and the Laboratory give ca. 1 second as the time difference of occurrences of the micro-tremors at the two stations, being earlier at the former station than at the latter, while the amplitudes were nearly the same at both stations. For a further study of the nature of the micro-tremors of the second kind, the micro-seismographs, Type G_A were installed at the Hondô observing room on Aug. 17, 1933, and were at work till Sept. 7, and the micro-seismographs, Type G_B were temporarily set up at stations surrounding the crater. The horizontal motion of the micro-tremors of the second kind observed at Suzuriisi was virtually in the direction towards the First Crater, and the vertical motion was about 1.2 times the horizontal, the upward motion being in the phase of the NW-ward motion in the horizontal plane. The amplitude of the micro-tremors recorded at Hondô was 2.7 times that at Suzuriisi and the phase of waves was opposite at the two stations, the pull phase of every wave of the micro-tremors at Suzuriisi corresponding to the push phase at Hondô. But the wave-forms were quite similar at the two stations both as regards amplitude and period, and thus the identification of the corresponding phases of waves was made without much difficulty. The horizontal displacements of the micro-tremors of the second kind observed at Sara-yama were in the direction S10°E–N10°W and the vertical displacements were about twice as great as the horizontal, the upward motion being in phase with the corresponding S10°E-ward motion. The amplitude here recorded was about 1.6 times that recorded at Hondô, the westward phase at the latter station corresponding to the southward phase at Sara-yama. At Taka-dake, the horizontal displacements of the micro-tremors of the second kind were observed to be in the direction N77°E–S77°W. The amplitudes and periods here recorded were nearly the same as those recorded at Hondô, the eastward phase at Taka-dake corresponding to the westward at Hondô. Thus the directions of the horizontal displacements, their relative amplitudes and the corresponding phase of waves of the micro-tremors

of the second kind at the six stations were as given in the following Table 7, and Fig. 15 shows graphically the results of observations.

Table 7

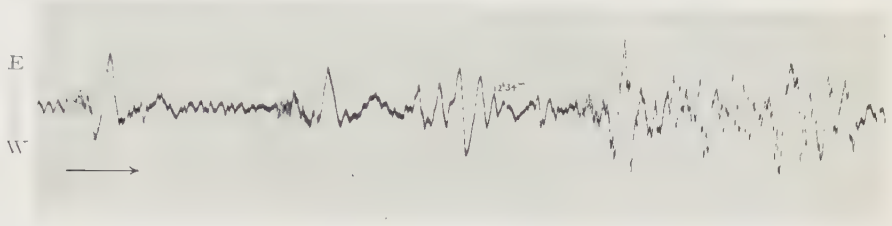
Station	Direction of horiz. disp.	Phase	Relative amplitude	V/H
The Laboratory	E–W	push	1	1.0
Miyadi	NNE–SSW	?	1	
Hondô	S74°W–N74°E	push	2.5	1.1
Suzuriisi	SE–NW	pull	0.9	1.2
Sara-yama	S10°E–N10°W	push	4.0	2.0
Taka-dake	N73°E–S73°W	push	2.5	

Fig. 15. Distribution of the direction of the horizontal displacement, the relative amplitude and the corresponding phase of the micro-tremors of the second kind.



Now, we come to the consideration of the origin of the disturbances of the micro-tremors of the second kind. It seems to lie immediately under the crater at a depth of 1 or 2 km. which is roughly determined from the observed facts above described. The horizontal displacement of the micro-tremors being practically confined to the direction of propagation at all observing stations, it should consist of a kind of longitudinal waves generated at the origin, the mode of oscillation being defined by the observed facts. Fig. 16 shows a portion of a record of eruption-earthquakes registered by the micro-seismographs, G_A at Hondô. The quick vibrations in the record of the eruption-earthquakes are followed by one complete large wave, the period of which is about 6 seconds and the direction of displacement is confined to the direction S74°W–N74°E, moving at first to S74°W upwards and then to N74°E downwards. This long wave may, so it seems to me, be considered as having been generated by the upward

Fig. 16. The eruption-earthquakes of the First Crater on Aug. 17, 1933 registered by the micro-seismograph, G_A, at the Hondô observation room. (Time between two consecutive marks = 1 min)



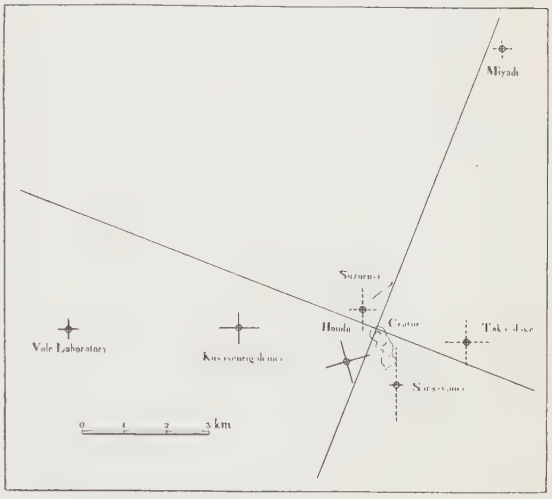
(4/5×the original record)

mass movement to fill the space evacuated by the eruption. Since the eruption is estimated as occurring at about 1 km. depth, the initial displacement of the wave generated by the mass movement should be in push phase at near stations such as Hondô, which was not contrary to the observed fact. The mode of oscillation of the micro-tremors of the second kind is quite similar to that of the wave of an eruption-earthquake such as has just been described, and a similar mechanism of mode of occurrence is to be considered as probable. The distribution of the relative amplitude and the corresponding phase of the micro-tremors of the second kind given in Fig. 15 leads us to a consideration of a magmatic reservoir containing gas-riched magma in the active period of the volcano, which is set into vibration by some internal eruptive disturbance and generates spherical waves, whose principal phases propagating with the velocity of Rayleigh waves. But, to determine the mode of oscillation of the magmatic reservoir, the observing stations must be increased in number at different azimuths and different distances, and further investigation on this subject is now in progress, and the result will be reported on a subsequent occasion. If the mechanism of occurrence is as above supposed, the period of the micro-tremors of the second kind should be dependent on the dimensions of the magmatic reservoir and on the internal conditions of its contents. The observed period should thus have an intimate relation to the state of activity of the volcano. Actually, the periods of the micro-tremors of the second kind observed in the case of an isolated group of small eruptions of the Fourth Crater, the southernmost of the four craters, during Sept. 5–8, 1930, were less than 4 seconds, while in the case of the great explosive eruptions in 1932 and 1933 of the First and the Second, the northern two of the four craters, they were about 6 seconds and sometimes even more than 8 seconds as will be described in Part II of the present study.

7. The volcanic micro-tremors of the third kind

The micro-tremors which the writer calls the "third kind," and the period of which ranges from 0.4 to 0.6 sec., were observed only in active times of the volcano. The movements of the micro-tremors of this kind recorded at the Volcanological Laboratory are a continuous train of somewhat regular waves, constantly changing their directions of vibration. The mean amplitude of the tremors is nearly the same for the N–S and E–W components, and that of the vertical component is less than one-tenth of that of the former. Fig. 17 in Plate II is a reproduction of the record of the micro-tremors of the third kind obtained by the short period micro-seismographs, S_R on Sept. 10, 1932 at the Laboratory. As will be seen in the record, the micro-tremors of the third kind change their amplitudes at irregular intervals, which is an interesting phenomenon of these micro-tremors showing a certain intimate relation between the tremors and the activity of the volcano. When observed in the pit of ca. 20 m. depth, the amplitude of the micro-tremors reduces to about 0.6 of that observed at the surface of the ground, as is to be expected from the shortness of the periods. The mean amplitude recorded at Kusasenrigahama was twice as great as the corresponding mean amplitude simultaneously recorded at the Laboratory, the amplitude of the E–W component being 1.2 times that of the N–S component. At Hondô the mean amplitude of the micro-tremors of the third kind was the same for the N–S and E–W components, and that of the vertical component was about half that of the horizontal. The value for Hondô was 2.2 times that simultaneously observed at the Laboratory at the foot. At Suzuriisi the horizontal displacements of the tremors were very small as compared with those recorded at Hondô, and their N–S component was about 1.2 times of the E–W component, while at Sara-yama, they were exceedingly great as compared with those observed at Hondô and the vertical displacements recorded were as pronounced as the horizontal. The recorded mean amplitude of the N–S component at Sara-yama was about 5 times that of the E–W component. The horizontal displacements of the tremors under consideration observed at Takadake were the same both in the N–S and in the E–W component, while at Miyadi the N–S component was slightly greater than the E–W component. The distribution of the relative amplitude and the ratio of the mean amplitude of the N–S component to that of the E–W component observed at the above 7 stations are given in Fig.

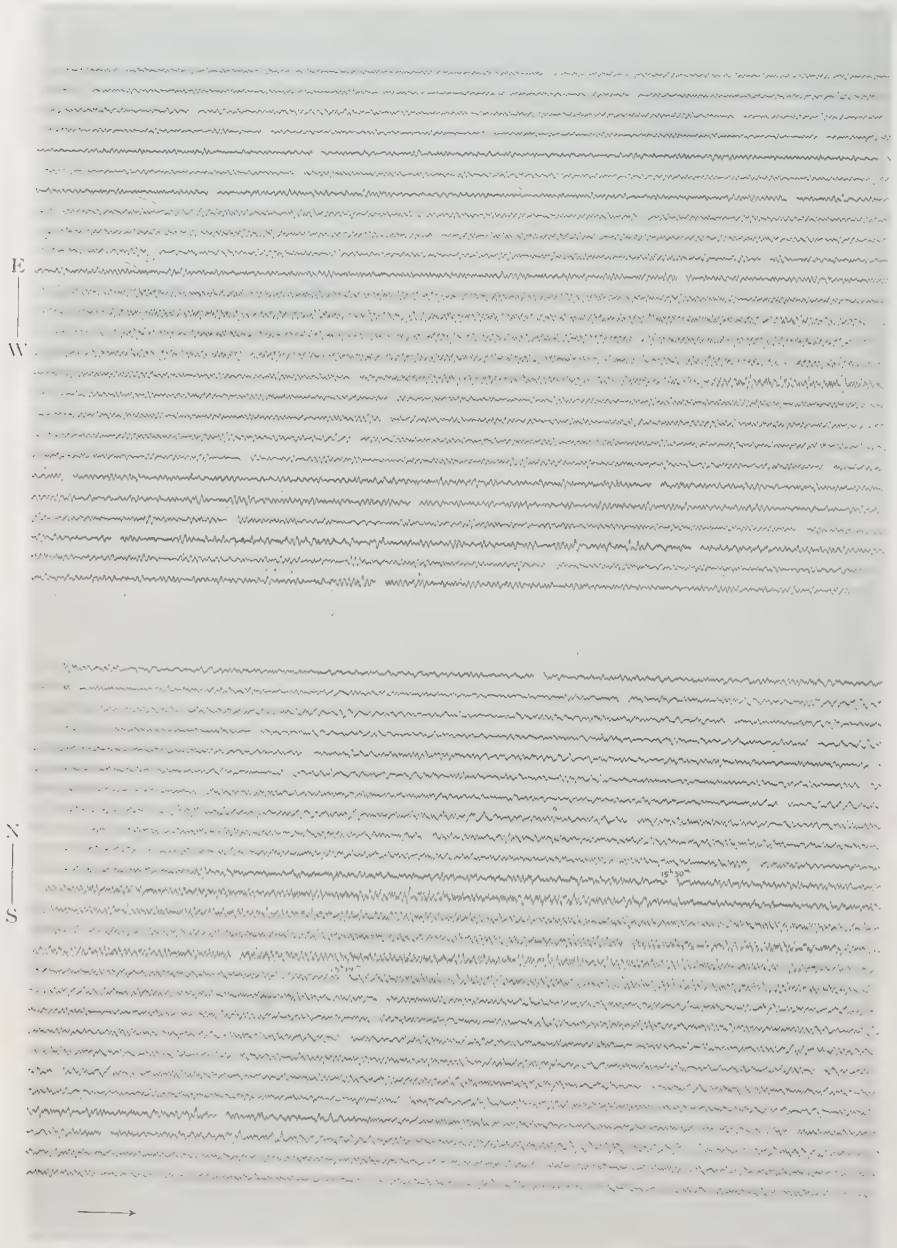
Fig. 18



18. The micro-tremors of the third kind being of short wave length of probably about 500 m., they are greatly disturbed by the geological irregularities of the district. Moreover the mode of oscillation recorded is very complex, which is probably due to the superposition of two different kinds of micro-tremors of nearly the same amplitude, one being micro-tremors of the third kind and the other of the first kind; consequently the directions of the vibrations of the micro-tremors observed could not be determined, but the distribution of the observed amplitudes given in Fig. 18 seems to throw some light upon the mechanism of their occurrence. As shown in the record reproduced in Fig. 20, the principal large vibrations of the eruption-earthquake resemble the micro-tremors of the third kind both in period and in mode of oscillation. According to the theory[1] that the Rayleigh wave has a certain azimuthal distribution of displacement, the transversal component of displacement, in the vicinity of the origin of disturbance, is large as compared with the longitudinal and vertical ones occurring close to certain specified lines of direction, whereas at increasing distances from these specified lines of direction, the latter become large as compared with the former. This property of the Rayleigh wave is in accord with the observed distribution of the horizontal and vertical displacements. Thus it seems that the micro-tremors of the third kind may be considered as a kind of Rayleigh waves generated by disturbances of Shida's crack type,[2] and it is very interesting to observe that the specified directions of the Rayleigh wave given in Fig. 18 are virtually coincident with those of the *P*-waves of the eruption-earthquakes given in Fig. 21.

1. H. Nakano; Geophy. Mag. **1** (1928), K. Sezawa; Bull. Eqke. Res. Inst. **6** (1929).
2. M. Hasegawa; Beit. z. Geophy. **27** (1930).

Fig. 19. The micro-tremors of the fourth kind, quick oscillations in the middle part of the record superimposed on those of the third kind, registered by the short period micro-seismographs, S_B, at the Volcanological Laboratory on Sept. 5, 1932. (Time between two consecutive marks = 1 min.)



(2/3×the original record)

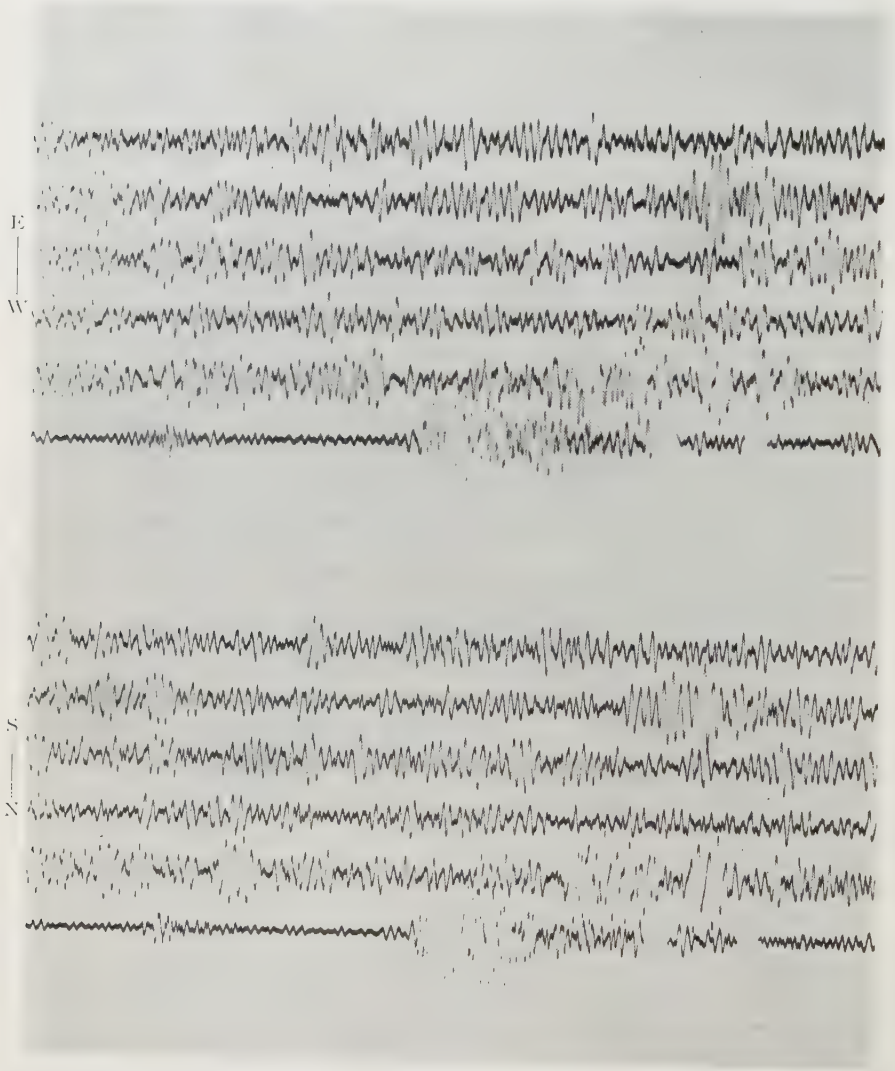
8. The volcanic micro-tremors of the fourth kind

Fig. 19 is a reproduction of a portion of the record obtained by the short period micro-seismographs, S_B, at the Aso Volcanological Laboratory on Sept. 5, 1932, where we see the quick oscillations of a period of ca. 0.2 sec. superimposed on the micro-tremors of the third kind. The amplitudes of the latter are much greater than those of the former, which are only about 0.05μ in double amplitudes. These quick oscillations, here called volcanic micro-tremors of the fourth kind lasted only for 30 minutes from 15^h14^m on Sept. 5, being the only occasion ever recorded clearly, and it is not yet certain whether the micro-tremors were due to volcanic disturbances or not, but it seems to the writer that they might have been due to volcanic disturbances at shallow depths under the crater. For, the time, when the micro-tremors were recorded, was the very time when the First Crater began, after a long repose, to emit black smoke more quickly, and with this exception, there was no disturbance that could be considered as the cause of the micro-tremors. Thus the micro-tremors may be supposed as due to the disturbance caused by the excavation of the volcanic pit, and fortunately on this unique occasion, the micro-tremors under consideration were recorded, without being masked by micro-tremors of the third kind of far large amplitude, which is not generally the case. At Hondô the recorded amplitudes of the micro-tremors of this kind seem to be of considerable magnitude, but the period of proper vibration of the ground being the same as that of the micro-tremors under consideration, it is very difficult to separate them. It will be very interesting to observe the micro-tremors of the fourth kind more closely, with a view to investigating the surface activity of the volcano, but suitable seismographs must be designed for the purpose.

9. The eruption-earthquake

Fig. 20 is a reproduction of the record of the eruption-earthquake of Aug. 16, 1933. It was registered by the short period micro-seismographs, S_A at the Hondô observation room. This eruption-earthquake was accompanied by an eruption of the First Crater, and volcanic fragments of medium size were ejected over the north wall of the crater. Eruptions of the First Crater of nearly the same strength continued for several days following. The recorded initial displacements of the eruption-earthquakes observed at Hondô and Suzuriisi on this occasion are given in Table 8. Of these, only the four cases

Fig. 20. The eruption-earthquake of Aug. 16th 23h 12m, 1933 registered by the short period micro-seismographs, S_A, at the Hondô observation room. Tremors continuously recorded in the record are the volcanic micro-tremors of the third kind.



20 sec.

(4/5×the original record)

given in Table 8, (C) were simultaneously observed at the two stations. But, since, without a single exception, the initial displacements, recorded at Hondô, are directed away from the crater while those at Suzuriisi are directed towards the crater it may be inferred

Table 8

(A) Hondô

Time of occurrence	A_N	A_E
	mm.	mm.
Aug. 16 23^h12^m	−3.8	−2.8
14	−1.4	−2.0
17 12 28	−1.4	−3.5
29	−3.0	−4.0
31	−1.2	−1.7
32	−1.0	−1.1
34	−2.0	−1.3
36	−3.0	−2.2
37	−5.0	−3.2

(B) Suzuriisi

Time of occurrence	A_N	A_E	$P \rightarrow B$
	mm.	mm.	sec.
Aug. 18 2^h31^m	−2.0	1.3	2.4
33	−1.3		2.0
34	−2.0		2.0
36	−3.0		2.4
37	−2.2		2.4
38	−1.4		2.4
39	−2.0	1.2	2.4
4 29	−2.5	1.4	2.2
31	−3.5	1.8	2.5
32	−3.0	1.5	2.8
33	−2.5	2.0	2.5
		Mean	2.36

(C)

Time of occurrence	Hondô	Suzuriisi	
	A_E	A_N	A_E
	mm.	mm.	mm.
Aug. 18 6^h31^m	−0.5	−1.5	1.1
33	−0.3	−2.0	
34	−0.7	−3.0	1.7
35	−0.4	−2.0	2.0

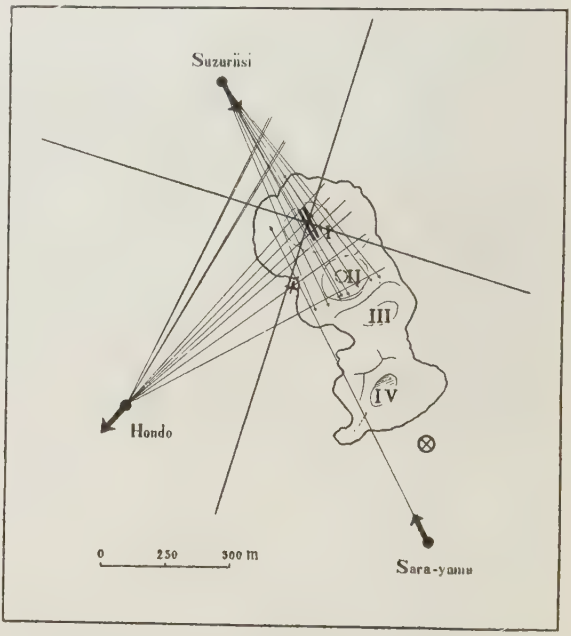
that the initial displacements of all the eruption-earthquakes given in the table are similar in character. From the observed directions of the initial displacements shown in Fig. 21 it is supposed that the hypocenters of the eruption-earthquakes lie approximately on a line connecting the four active craters. A single case of an eruption-earthquake was recorded at Sara-yama on Aug. 27, 1933. Its initial displacement was 5.2 mm. northward, 2.7 mm. westward, and 7.0 mm. downward on the record and its direction is shown in Fig. 21. The initial motions of the *S*-waves of eruption-earthquakes recorded at Hondô are directed to NNW. All these observed facts of the eruption-earthquakes are fairly well explained by taking them as instances of Prof. Shida's crack type, and the nodal lines as given in Fig. 21. It is also very interesting to consider the formation of the row of the present active craters in connection with the fact that the direction of cracks of the eruption-earthquakes is parallel to the row of craters, and moreover the cracks themselves lie side by side on the line joining the crater. The mean depth of the eruption-earthquakes was determined from the following data;

1. The mean real emergent angle observed at Hondô = ca. 40°. The mean epicentral distance from the Hondô obs. room = 1 km. The depth,

assuming the straight path of the seismic ray = 0.84 km.

2. The mean duration of preliminary tremors observed at Hondô = 1.0 sec.. The mean duration of preliminary tremors observed at Suzuriisi = 0.8 sec.. The mean epicentral distance from the Hondô obs. room = 1 km. The mean epicentral distance from the Suzuriisi obs. station = 0.6 km. The depth, assuming the straight path of the seismic ray = 0.88 km. Taking the mean, the mean depth of the eruption-earthquakes was taken as about 860 m.

Fig. 21. Distribution of the initial motions of the eruption-earthquakes of the First Crater in Aug. 1933.



The velocities of propagation of the seismic waves in the district were determined by the following observed data of a volcanic earthquake on Oct. 22, 1932:

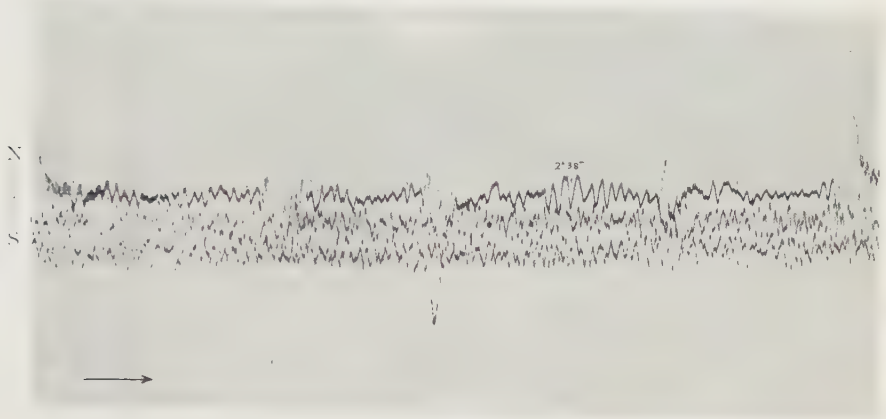
Station	Time of occurrence		P–S	$\bar{e}$	Δ
	P	S			
			sec.		km.
The Hondô obs. room	$12^h0^m11.8^s$	$0^m12.5^s$	0.7	29°	0.8
The Volc. Laboratory	16.8	18.9	2.1		7.05

The position of the epicenter is given by the cross in Fig. 21, the depth of the origin, using the observed data of the eruption-earthquakes, being calculated as about 450 m.. The velocities of the seismic waves determined are as follows:

The velocity of the P-wave: 1.25 km./sec. The velocity of the S-wave: 0.98 km./sec. The velocity of the Rayleigh wave: 0.90 km./sec.

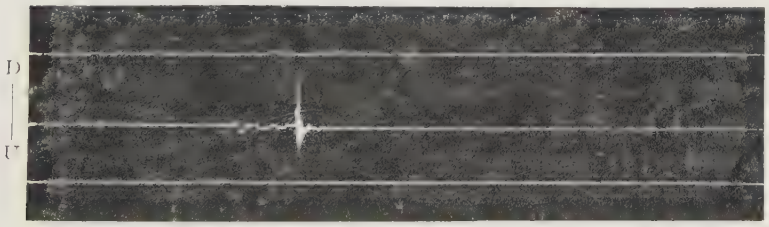
Fig. 22 shows a portion of the record obtained by the microseismographs, G_R, at Suzuriisi on Aug. 18, 1933. Five eruption-earthquakes are recorded on it. The large displacements following the quick vibrations of the eruption-earthquakes are due to the sound

Fig. 22. Five eruption-earthquakes registered by the micro-seismographs, G_R, at Suzuriisi on Aug. 18, 1933. The large displacements following the quick vibrations of the eruption-earthquakes are due to the sound shocks of the eruptions.



shocks of the eruptions. The time differences between the sound shocks and the initial motions of the eruption-earthquakes are 2.36 seconds in the mean at Suzuriisi, and appear in the last column of Table 8 (B). The time taken by the *P*-wave to travel 1.05 km., taking the depth of the earthquake 850 m. and the epicentral distance 600 m., is 0.84 seconds and the time taken by the sound-shock to travel 700 m. is 2.05 seconds, taking the velocity of sound as 340 m./sec. for mean air temperature of 15°C. Accordingly the time taken by the sound-shock to travel from the origin of the earthquake to the mouth

Fig. 23. The eruption-earthquake and its sound shock of March 4th 19h 49m, 1933 registered by the Wiechert vertical component seismograph at the Volcanological Laboratory.



(Full size the actual)

of the volcanic vent is to be taken as 1.15 seconds, from which the velocity of the sound-shock in gas-riched molten lava in the vent—the author observed red hot lava swelling up at its mouth—is calculated as about 790 m./sec.. Fig. 23 is a reproduction of the record of an

eruption-earthquake and of its sound-shock, registered by the Wiechert vertical component seismograph at the Volcanological Laboratory, 7.3 km. from the crater on March 4, 1933. The time differences between the initial motions of the principal phases of the eruption-earthquakes and their sound-shocks recorded by the same instrument on March 4, 1933, are given in the following Table 9;

Table 9

Time of occurrence	L_Z	B_Z	$L \rightarrow B$
	mm.	mm.	sec.
March 4 11^h43^m	−0.5	−0.7	15.5
$18^{\ }\ 57$	−0.3	−0.6	15.5
19 07	−0.4	−0.8	16.0
10	−0.1	−0.7	15.6
49	−0.8	−2.1	15.8
Mean			15.68

L_Z: Amplitude of the recorded initial motion of the principal phase of the eruption-earthquake.
B_Z: Amplitude of the recorded initial motion of the sound-shock.
$L \rightarrow B$: The time difference between the two phases.

The durations of preliminary tremors of large eruption-earthquakes observed at the Laboratory being 2.0 seconds in the mean, the time difference of occurrence between the *P*-waves and the sound-shocks of the eruption-earthquakes is 17.7 sec. in the mean. The time taken by the *P*-wave to travel 7.3 km. is 5.85 seconds, and that taken by the sound-shock to travel 7.5 km., 22.43 seconds, taking the velocity of the sound wave as 334 m./sec. at a mean air temperature of 5°C. Accordingly the time taken by the sound-shock to travel from the origins of the earthquakes to the mouth of the vent of the crater, where the air wave is considered as starting, is 1.1 seconds, which value is nearly the same as that obtained at Suzuriisi as described above. Although there are no observational data to determine directly the depth of the violent eruption-earthquakes of the Second Crater in spring, the above fact seems to indicate that the depths of the eruption-earthquakes did not differ greatly in the two cases. The eruptions of the Second Crater in Feb. and March 1933, were exceedingly violent, abundant quantities of lava blocks being ejected, some of them exceeding 20 tons in weight and being thrown 900 m. or even more in horizontal distances, while in the summer of the same year the eruptions were confined to the First Crater, and were feeble, only a few blocks of lava of about 0.1 ton weight being thrown out to horizontal distances of 100 m. or less. The initial velocities of the lava blocks projected were estimated at about 94 m./sec. in the case of the eruptions in the early spring of 1933 and at about 30 m./sec. in the case of the eruptions in Aug. of

the same year. If we take the pressure difference p between inside and outside the vent, which gives the initial velocity V to the lava block of density ρ, we have $p = 1/2 \times \rho V^2$, the pressure change due to the mass displacement being neglected. The equation gives a pressure difference of about 108 atmospheres for the case of the early spring of 1933, and about 9 atmospheres for the case of the summer of the same year, the former value (108 atms.) corresponding to a pressure at a depth of about 450 m. and the latter value (9 atms.) to a depth of about 37 m.. The density ρ is assumed as 2.5. We have seen that the depth of the eruption-earthquakes, being about 860 m., were not very different in the two cases. But the spring eruptions of the Second Crater were so exceedingly violent that the initial velocity of the ejected mass corresponded to the pressure at a depth of 450 m., while the summer eruptions of the First Crater were so feeble that the initial velocity of ejecta corresponded to the pressure at a depth of only 37 m.. Thus the depth at which the eruption starts seems to be roughly independent of the strength of the eruption and the cause of this apparent discrepancy seems to lie in that, in the case of small

Fig. 24. An eruption of the Second Crater at about 15^h on Feb. 24, 1933, taken at (A) in Fig. 25.

scale eruption, the quantity of volcanic gases explosively evolved from the magma to cause the eruption is not sufficient to maintain a constant pressure on the mass to be ejected. Thus the quantity and the initial velocity of lava blocks thrown out are to be taken as being mainly

due to the quantity of volcanic gases explosively evolved from magma at the eruption and not to the depth at which the explosive expansion of volcanic gases occurs. Fig. 24 shows an eruption of the Second Crater at about 15^h on Feb. 24, 1933 photographed at *A* on a hill, west of, and about 250 m. distant from the crater, as shown in Fig. 25. The height of the volcanic ejecta seen in the photograph may be estimated from the fact that the height of the palisades is about 1 meter. The height of the crater rim above the mouth of the vent is roughly about 70 meters.

As will be seen from the photograph, the greater part of the lava blocks thrown out from the Second Crater in the early spring eruptions of 1933 fell upon the southern sides of the vent forming new steep slopes of lava blocks and fragments on the inner side of the southern wall of the crater. The horizontal distribution of the ejecta thrown out from the Second Crater is exceedingly eccentric with respect to the vent of the crater. This eccentric distribution of the volcanic ejecta seems to the author to be mainly due to the southward inclination of the vent of the Second Crater, while the vent of the First Crater is practically vertical, the horizontal distribution of the ejecta thrown out from the latter being nearly circular, the center of the circle lying in the vent. From the above considerations the main magmatic reservoir, which was active in 1932 and 1933, is concluded as lying immediately under the First Crater, and as coinciding with the origin of disturbance determined from the observations of the volcanic micro-tremors described in the preceding pages.

Fig. 25. Distribution of lava blocks thrown out from the First and the Second Craters in Feb. and March 1933.

10. Summary

From observational data on volcanic micro-tremors and eruption-earthquakes at Aso which were obtained by the present author with specially prepared seismographs, and considerations based on them, the following results were obtained:

1. There are four kinds of volcanic micro-tremors observed at the Volcano Aso.

2. The volcanic micro-tremors of the first kind, the period of which is about 1 second, form a kind of Love wave having a certain azimuthal distribution generated by internal eruptions of volcanic gases, and with a velocity of propagation of about 1.0 km./sec..

3. The distribution of amplitudes of the micro-tremors of the first kind observed during the active time of the volcano in Oct. 1932 is satisfactorily explained by Nakano's solution of the Love wave, taking $n=2$ in his equation, while in a repose time we have to take $n=1$ to explain the observational facts. The depths of the origin of disturbances are also different in the two cases, deeper for the former case than for the latter.

4. When the volcano is quiescent the micro-tremors of the first kind occur not in continuous trains, but intermittently, several wave groups of ca. 1 micron or less in double amplitudes per hour, but in an active time they become continuous trains of irregular waves.

5. The amplitudes of micro-tremors of the first kind recorded by seismographs set directly on volcanic rock in the pit of ca. 20 m. depth are reduced to 0.85 of the corresponding amplitudes observed on a ground of volcanic ashes.

6. The volcanic micro-tremors of the second kind, the period of which ranges from 3.5 to 7 seconds, are a kind of Rayleigh wave having a certain azimuthal distribution generated by the oscillation of the magmatic reservoir, and the velocity of propagation is 0.90 km./sec..

7. Between amplitudes and periods of the micro-tremors of the second kind no definite relation was found, but the ratio of the recorded horizontal amplitude to the vertical increases as the period decreases.

8. In a repose time of the volcano the micro-tremors of the second kind occur not in continuous trains, but intermittently, several groups of regular waves of a few microns in double amplitudes per hour, while in an active time they become continuous trains of somewhat irregular waves.

9. The micro-tremors of the second kind are frequently observed

accompanied by those of the first kind, which latter are recorded from 0 to 20 seconds before the recorded initial phase of the principal part of the former, but sometimes they are observed independently of each other.

10. The volcanic micro-tremors of the third kind, the period of which is about 0.5 seconds, is a kind of Rayleigh wave having a certain azimuthal distribution generated by internal eruptions of volcanic gases.

11. The micro-tremors of the third kind are observed only in an active time of the volcano and change their amplitudes at irregular intervals, which bear some resemblance to pulses of volcanic rumblings and of emission of volcanic smoke.

12. The volcanic micro-tremors of the fourth kind, the period of which is about 0.2 seconds seem to be generated by some disturbances due to surface eruptions of the volcano.

13. The mechanism of occurrence of the eruption-earthquakes is of Prof. Shida's crack type.

14. The direction of cracks of the eruption-earthquakes observed is parallel to the row of the present active craters, and moreover the cracks themselves stand side by side on the line joining the craters.

15. The velocities of propagation of seismic waves in the district observed are 1.25 km./sec. for the *P*-wave, 0.98 km./sec. for the *S*-wave, and 0.90 km./sec. for the Rayleigh wave.

16. The velocity of propagation of sound-shocks in gas-riched molten lava in the volcanic vent is calculated from observed time differences between the eruption-earthquakes and the sound-shocks at about 790 m./sec..

17. The depths of eruption-earthquakes observed, being about 860 m., were not very different in the two cases, one of which is the case of exceedingly violent eruptions of the Second Crater in the early spring of 1933, the initial velocity of lava blocks projected being about 94 m./sec. and the other, of feeble eruptions of the First Crater in the summer of the same year, the initial velocity of the ejecta being only about 30 m./sec..

18. The quantity and the initial velocity of lava blocks thrown out from the vents are mainly due to the quantity of volcanic gases explosively evolved from the magma and not to the depth at which the eruption-earthquake occurs.

19. The volcanic vent of the Second Crater is inclined towards

the south. The magmatic reservoir which was active in 1932 and 1933 seems to be just under the First Crater, coinciding with the origin of disturbances determined from the observations of the volcanic micro-tremors.

In conclusion, the writer wishes to express his thanks to Prof. Toshi Shida for his invaluable advice and to Mr. I. Yasuda who assisted in preparing some of the seismographs.

APPENDIX

Micro-tremors caused by Rainfalls

On rainy days our sensitive seismographs set up at the Aso Volcanological Laboratory frequently recorded small micro-tremors of a few microns in double amplitudes, their periods being about 0.5 seconds. A typical record of the micro-tremors registered by the short period micro-seismographs, S_A, on July 21, 1931 has been reproduced in Fig. 26, Plate II. The oscillatory motions of the micro-tremors of this nature are very smooth and regular, continuing in nearly the same amplitudes for many hours, as compared with those of the volcanic micro-tremors of the third kind which are of the same period and were described in the preceding paper. The oscillatory motions of a particle of the ground of the micro-tremors are very complex as will be seen in the record. The vertical motion of the micro-tremors recorded was about one-third of the horizontal motion. The period observed in the N-S component in the record is 0.46 seconds while that in the E-W component is 0.54 seconds. This difference in period should not be considered as simply due to the difference in amplitude, or to the difference in the periods of proper oscillation of the ground at the observing station, but may be due, as will be explained in the following pages, to the difference of the origins of disturbance generating the micro-tremors. The mean amplitudes of the micro-tremors and the amounts of precipitation observed at the Aso Volcanological

Laboratory during June 30–July 19, 1931 are given in the following Table 10 and shown in Fig. 27.

Table 10

Date	0^h-4^h			4^h-8^h			8^h-12^h			12^h-16^h			16^h-20^h			20^h-0^h		
	A	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*
	μ		mm.	μ		mm.	μ		mm.	μ		mm.	μ		mm.	μ		mm.
June 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.3
July 1	0	0	20.4	0.6	6.8	27.5	1.6	18.6	0.2	2.1	19.4	0.1	1.9	13.7	1.7	2.2	9.2	6.3
2	2.0	6.3	58.2	1.5	22.5	6.4	1.0	31.4	0	0.5	24.0	2.6	0	17.0	0	0	10.0	0
3	0	1.6	0	0	0.6	2.3	0	1.4	0.9	0	1.1	5.4	0.2	2.5	2.4	0.2	3.6	0.7
4	0.2	2.8	0.6	0	2.2	7.2	0	3.5	0.5	0	3.9	3.4	0	3.6	4.3	0	4.5	1.5
5	0	4.9	0.3	0	3.7	0.9	0	2.2	0	0	1.0	0.5	0	0.7	1.0	0	0.9	0.9
6	0	1.0	41.0	1.6	14.0	41.0	2.9	32.0	35.2	4.0	43.8	50.5	5.5	52.8	14.4	4.5	52.3	58.2
7	4.4	63.9	29.7	4.2	55.6	8.8	4.0	43.6	35.5	3.5	39.6	15.2	3.9	36.2	0	3.6	23.7	0
8	2.5	14.1	0	1.0	7.2	0	0.2	1.8	0	0	0	0	0	0	0	0	0	0
9	0	0	1.1	0	0.5	5.5	0	2.6	6.2	0	5.3	0	0	5.1	0	0	3.7	11.5
10	0.5	5.8	33.9	2.0	17.0	40.1	2.9	33.0	4.3	2.0	33.0	0	2.4	24.5	0.8	1.1	14.0	5.4
11	1.0	7.6	8.2	0.6	6.0	9.6	1.1	8.7	16.5	1.6	8.8	6.0	0.6	15.2	1.4	0	12.0	0
12	0	7.7	0	0	4.1	1.5	0	1.7	6.7	1.2	3.2	49.9	2.5	19.7	53.7	3.9	41.7	3.5
13	4.7	44.0	12.3	3.4	35.6	1.7	1.6	25.0	0	0.6	12.0	0.1	0	3.5	0.3	0	1.8	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0.8	3.8	0	2.1	1.5
17	0	3.0	0	0.4	2.3	0.3	1.6	1.6	11.6	2.3	4.7	0	2.1	5.7	14.2	1.7	9.0	0.4
18	1.2	9.0	0	0.8	7.4	2.2	0.6	4.5	0	0.5	2.7	0	0.3	0.7	0	0	0.3	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A: The E-W component of the mean amplitudes of the micro-tremors. *F*: The calculated amounts of water flowing in the rivers in an arbitrary unit. *P*: The amounts of precipitation.

Fig. 27. Relation between the mean amplitudes of the micro-tremors and amounts of precipitation, and the estimated amounts of water flowing in the rivers.

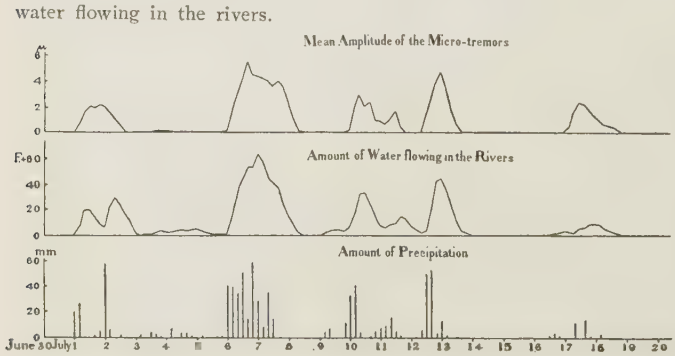


Fig. 27 shows how the observed amplitudes of the micro-tremors depend on the amounts of precipitation at Aso, and suggests that they are generated by some dis-

turbances caused by the rainfalls. The waters of the two valleys, the Aso valley in the north and the Nangô in the south, flow down through the rivers, Kuro-kawa and Sira-kawa respectively, falling in finally to the two famous waterfalls of Sugaru in the former and Aigaeri in the latter. The waterfall of Sugaru, with a head of ca. 30 meters, is at a distance of 1.73 km. to W10°N and that of Aigaeri, whose head is ca. 20 meters, at a distance of 2.35 km. to S38°W from our Volcanological Laboratory as will be seen in Fig. 1 of the preceding paper. Though the amounts of water flowing in the rivers were not observed, their relative variation with respect to time may be roughly estimated from the amount of the precipitations. But, strictly speaking, the amount of water flowing in a river will depend not only on the amount of precipitation but also on its rate, and it is not an easy task to estimate the amount of flow of water from the amount of precipitation. In the present case a rough estimation was carried out on the assumption that the amount of water flowing in the rivers increases rapidly with rainfalls and attains a maximum about 6 hours after the rainfall, and then gradually decreases for 18 hours. The amounts of water flowing in the rivers thus estimated in an arbitrary unit are given in the F-column in Table 10 and shown in Fig. 27. The parallelism of the curves of the amplitude of the micro-tremors and the estimated amount of flow in the rivers in Fig. 27 seems to show that the micro-tremors are generated mainly by the two waterfalls and partly by the rushing streams in the rocky rivers. Thus the observed complexity of the mode of oscillations of the micro-tremors at the Laboratory is probably due to the superposition of different waves, one coming from the Sira-kawa in the south, and the other from the Kuro-kawa in the west, each component of them itself being not simple from the nature of the tremors. If the micro-tremors could be taken as kinds of Rayleigh wave propagated from the origins of disturbance, the horizontal displacements should be confined practically to the E-W component for the micro-tremors generated by the Sugaru waterfall, and should roughly have the same amplitude for both N-S and E-W components generated by the Aigaeri waterfall. Further the amplitude of the micro-tremors generated by the latter waterfall and observed at the Laboratory is to be estimated at about 0.6 of that of the micro-tremors caused by the former waterfall, taking into consideration two differences (a) that between the head of the waterfalls and (b) that between their distances from the laboratory. These reasons

Table 11

Hour	A_E	A_N	A_E/A_N	T_E	T_N	T_N/T_E
	μ	μ		sec.	sec.	
July 6 10h—12h	0.25	0.26	0.97	0.51	0.49	0.96
14 —16	0.55	0.43	1.28	0.58	0.56	0.96
16 —17	0.65	0.52	1.25	0.61	0.54	0.88
17 —18.5	0.65	0.52	1.23	0.59	0.54	0.92
21 —23	0.65	0.50	1.30	0.59	0.54	0.92
7 0 — 2	0.60	0.55	1.09	0.56	0.52	0.93
6 — 8	0.31	0.35	0.90	0.55	0.51	0.93
9 —11	0.35	0.35	1.00	0.55	0.50	0.91
15 —17	0.17	0.21	0.83	0.53	0.51	0.94
20 —22	0.60	0.48	1.23	0.57	0.54	0.95
8 7 — 9	0.70	0.58	1.20	0.61	0.56	0.92
12 —14	0.70	0.55	1.28	0.55	0.54	0.98
9 7 — 8	0.36	0.40	0.90	0.54	0.51	0.94

Amount of precipitation

Hour \ Day	6	7	8	9
	mm.	mm.	mm.	mm.
0h	0.0	0.6	17.5	3.5
1	0.2	0.4	18.0	6.0
2	1.0	0.8	4.0	7.0
3	0.8	2.4	5.0	5.0
4	0.2	1.0	0.0	2.0
5	0.0	0.0	0.2	1.5
6	1.0	0.0	0.1	0.2
7	2.0	0.0	0.0	2.8
8	0.6	0.0	0.0	4.0
9	3.4	0.0	0.0	9.0
10	17.0	0.0	0.0	7.8
11	0.6	0.0	3.5	3.0

Hour \ Day	6	7	8	9
	mm.	mm.	mm.	mm.
12h	0.0	0.0	5.0	2.0
13	0.8	0.0	5.0	1.2
14	0.0	0.2	1.4	3.5
15	18.6	0.3	1.8	4.0
16	1.0	7.7	1.0	3.2
17	0.4	10.2	0.0	2.5
18	0.0	3.0	1.0	3.4
19	0.4	11.5	3.0	3.2
20	0.8	8.0	1.0	6.0
21	0.5	6.0	2.0	0.0
22	9.0	8.0	15.0	0.0
23	1.0	4.0	4.0	0.0

explain why the amplitude of the E-W component of the tremors is generally greater than that of the N-S component. But the bed of the river Sira-kawa being steeper than that of the river Kuro-kawa, the water falling in the Aigaeri waterfall increases sooner than in the Sugaru fall after a rainfall, so that the micro-tremors observed at the laboratory at very early stage of a rainfall of some duration may be explained as being mainly due to the Aigaeri waterfall. The results

of observations of the micro-tremors made with the short period micro-seismographs, S_B during July 6-10, 1932 were not contrary to this expectation as given in the foregoing Table 11 and shown in Fig. 28.

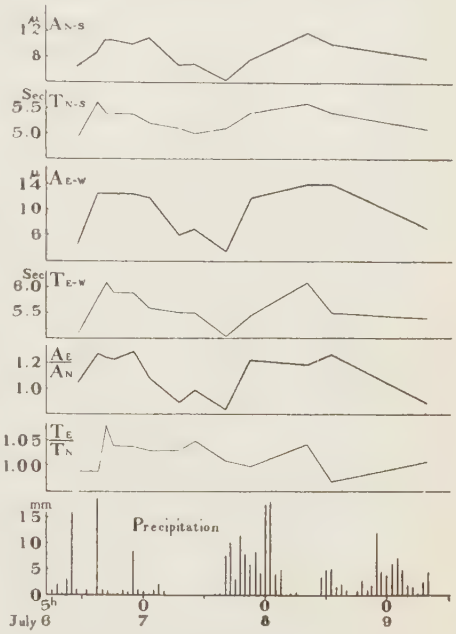


Fig. 28. Amplitudes and periods of the micro-tremors and amounts of precipitation.

The ratio of the amplitudes A_E/A_N in Fig. 28 shows that the horizontal displacements of the micro-tremors are predominant in the N-S component during the beginning stage of the rainfalls, but about five hours later, the two components become almost equal and the E-W component becomes predominant thereafter. The period varies in a similar way, but that of the N-S component is always slightly shorter than that of the E-W component. This is probably due to the difference in the head of the two waterfalls.

Summary

The micro-tremors observed at the Aso Volcanological Laboratory in and after rainy days are probably Rayleigh waves which are generated mainly by the two waterfalls, Sugaru and Aigaeri, in the river Kuro-kawa and Sira-kawa respectively. The period of the micro-tremors observed is about 0.5 seconds, being slightly shorter for the micro-tremors generated by the Aigaeri waterfall which is probably due to its smaller scale of disturbance.

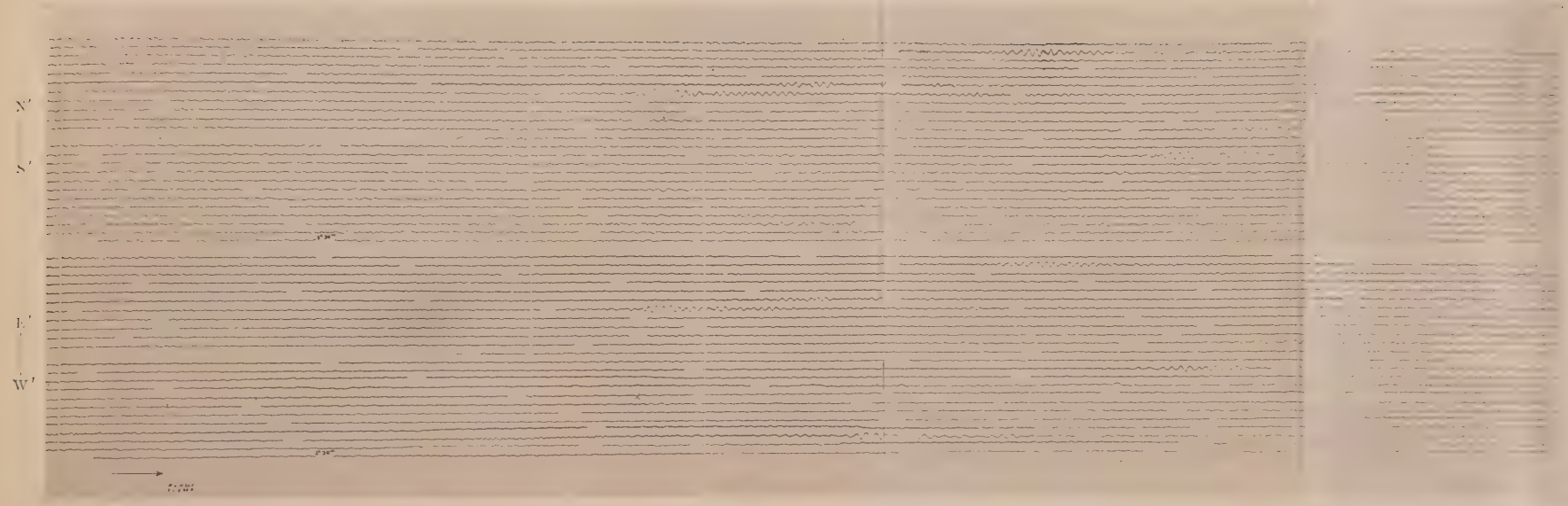


Fig. 6. A record obtained from the short period micro-seismographs, *Sn*, at the Aso Volcanological Laboratory on Nov. 28th 5^h30^m–6^h37^m, 1931 [illegible] quiescent and th[illegible] kind were recorded inter[illegible] (N'–N20°E, E'[illegible] consecutive marks—1[illegible]

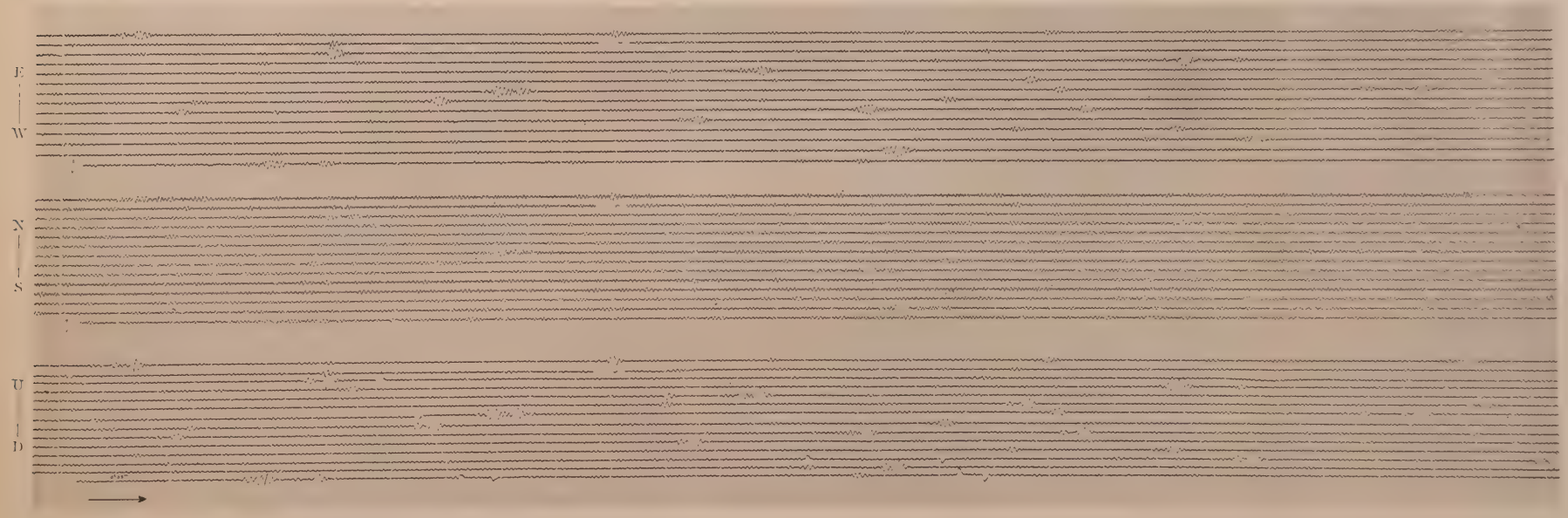


Fig. 10. A record obtained from the [illegible] at the Volcanological Laboratory on July 27th 0^h09^m–6^h42^m, 1932 when the volcano was quiescent and the micro-tremors of the second kind were recorded intermittently.
(Time between two consecutive marks[illegible] in.).

(1/3×the original record)

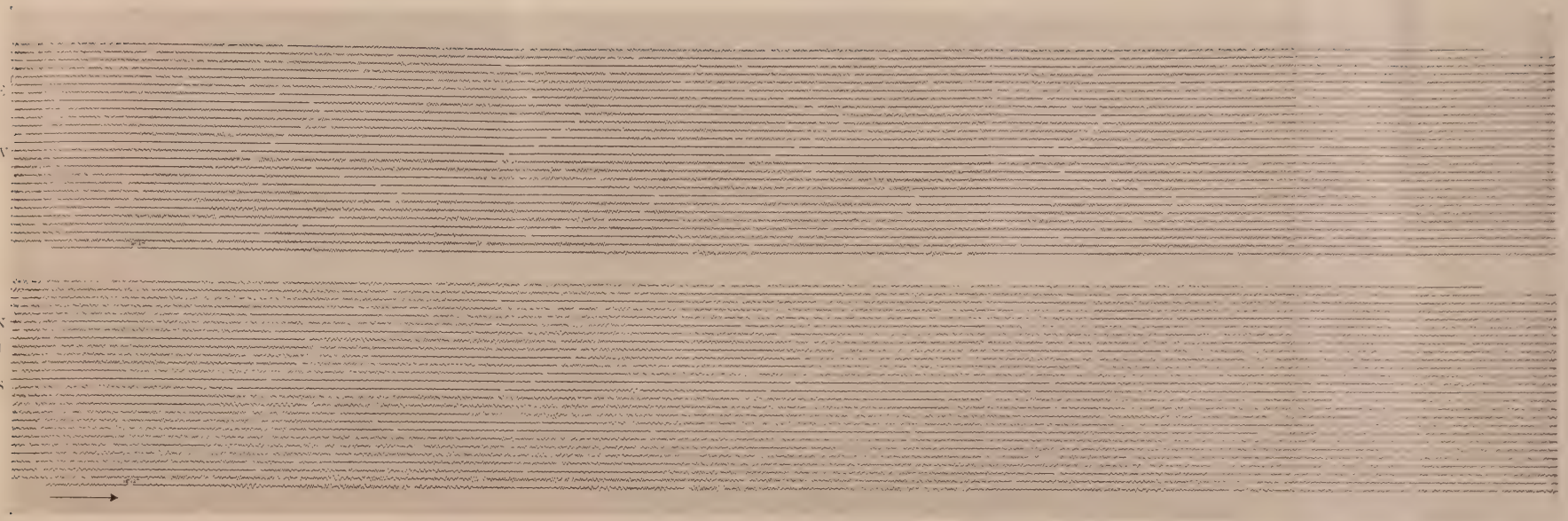


Fig. 17. The micro-tremors of the third kind registered by the short period micro-seismographs, S_B, at the Volcanological Laboratory on Sept. 10th 18h12m-20h49m, 1933 when the volcano was slightly active, constantly emitting black smoke from the First Crater.
(Time between two consecutive marks = 1 min.).

(1/3×the original record)

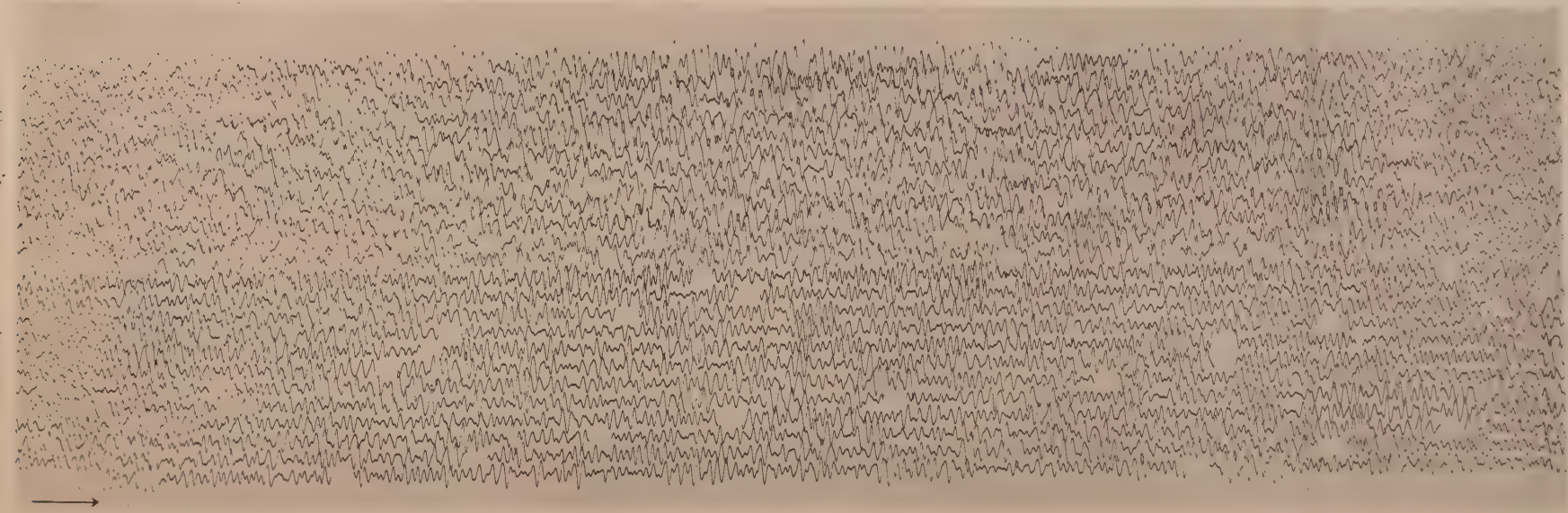


Fig. 26. The micro-tremors caused by rainfalls registered by the short period micro-seismographs, S_A, at the Volcanological Laboratory on July 21st 11h03m-11h26m, 1931.
(Time between two consecutive marks = 1 min.).

(1/3×the original record)

A Study on the Coastal Ground Water at Yumigahama, Tottori

By Yoshikazu Toyohara

(Received August 14, 1935)

Abstract

Several years ago we published a theory and model experiments on the contact surface of fresh- and salt-water under the ground near a sandy sea-shore and fortunately some interest was taken in our study by scholars in various countries. For the actual verification, the writer intended to make observations on a real coast perform, and recently carried out his intention at Yumigahama, Tottori Prefecture. The results show that our theory of coastal ground-water based on hydrodynamical considerations holds good for the actual sea-shore as well as for model experiments.

§ 1. Introduction

One of the most interesting and practical problems of coastal ground water is the infiltration of sea-salts. Under the ground near the sandy sea-coast, a stratum of fresh water pouring into the sea from the land lies over a stratum of salt water, the state of equilibrium being maintained according to the respective specific gravities of the two layers. Herzberg[1] states, from the results of investigation in Norderney Island, that both fresh- and salt-water strata on such sandy hills are in a state of statical equilibrium, and that the depth of the contact surface of the two water layers can be determined from their specific gravities (ρ, ρ_0), and the height (y) of the water table from the sea level. He gives the following formula

$$y'\rho=(y'+y)\rho_0 \quad \text{or} \quad \frac{y'}{y}=\frac{\rho_0}{\rho-\rho_0} \qquad \cdots\cdots\cdots\cdots(1)$$

where y' denotes the depth of the contact surface from the sea level. But, in order to ascertain the form of the contact surface by Herzberg's equation only, me must observe the level of ground-water-table at innumerable points. Prof. Nomitsu[2] studied the problem from the hydrodynamical standpoint, and derived a formula for the shape of

1. J. f. Gasbel u. Wasservers. **44**, 815 (1901).
2. T. Nomitsu, Y. Toyohara and R. Kamimoto. These Memoirs, A, **10**, 279 (1927)

the contact surface and obtained the important result that the contact surface could be determined by measuring the level of the fresh-water table at any two points only. His formula is as follows. If we take the coordinate origin at the mean sea-level on the strand-line, and the x-axis in the horizontal direction landwards and denote by h_0, h_L and y' the heights of the water table at $x=0$ and $x=L$ and the depth of contact surface respectively, then the shape of the contact surface will be given by

$$y'^2 = H_0^2 + \frac{H_L^2 - H_0^2}{L} x \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

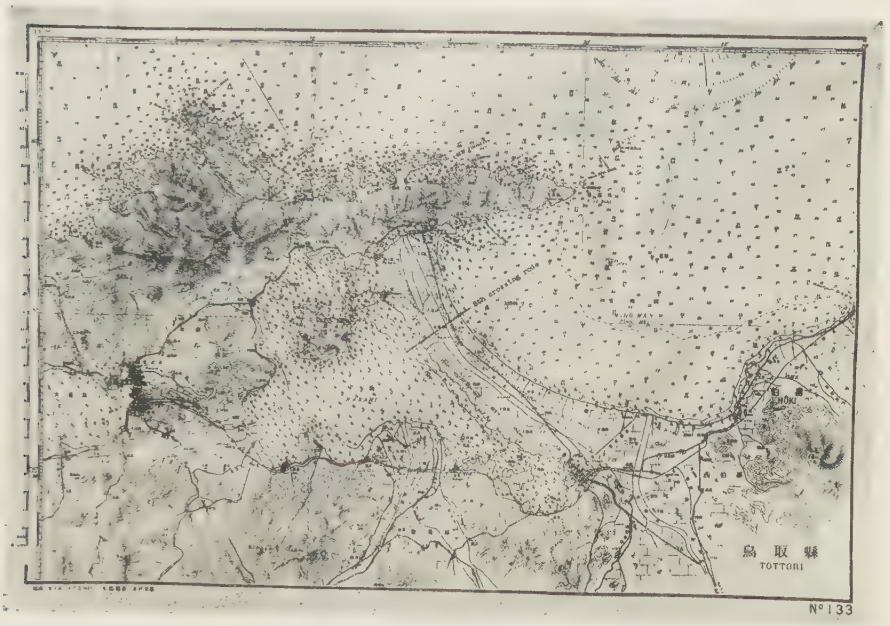
where $H_0 = \frac{\rho_0}{\rho - \rho_0} h_0$, $H_L = \frac{\rho_0}{\rho - \rho_0} h_L$. To verify this formula, the present writer with Mr. Kamimoto performed their model experiments in the laboratory, and got fairly concordant results. The theory and the model experiments were published in one paper in 1927. Then, the author was eager to complete the study by actual observations in a real coast, but the considerable expense involved prevented the execution of this plan for a long time. Fortunately, however, he got a grant from Nippon Gakujutsu Shinko-Kwai recently, and was able to perform several measurements at the coast of Yumigahama, Tottori Prefecture during about one year since July 1933.

The results of observation constitute this paper and show that our theoretical consideration is also valid for actual sea-coasts.

§ 2. Selection of Site for Experiments

To investigate the conditions in which fresh- and salt-water maintain equilibrium under the ground of the sea-coast, we must choose a place where the tidal effect is slight. Moreover, the best place is naturally a sandy coast where no rocks or other obstacles exist under-ground down to a sufficient depth. For these reasons we chose the coast of Yumigahama, Tottori Prefecture, facing the Japan Sea of small tide. This peninsula is a sandy bar about 18 kilometres in length and about 3 kilometres in width. The River Yone, an irrigation canal running along the central axis of the bar, always regulating the ground-water there. Thus this was a very suitable place for our experiments. Then, in order to find a suitable operating locality, we inspected the entire coast with the assistance of the Arable Land Section of the prefecture and neighbouring towns, and decided to operate along the fifth crossing road of the outside beach.

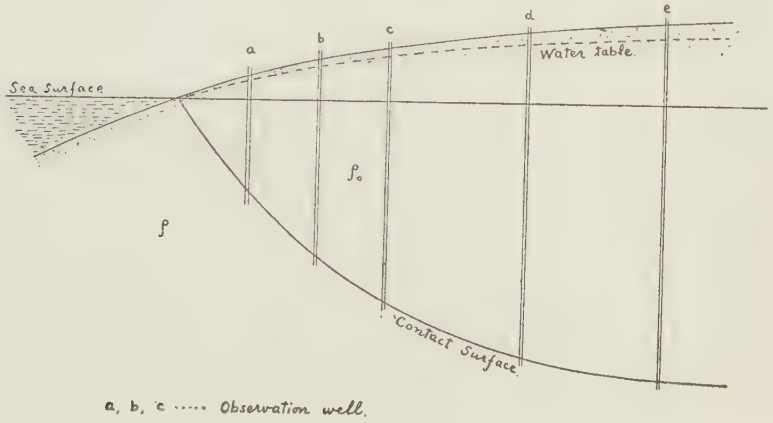
Fig. 1



§ 3. Method of Actual Experiments

We fix many observation points at various distances from the coast-line along the fifth crossing road in Yumigahama, and at each point drive an iron pipe of 2 inches diameter to make observation wells as shown in Fig. 2. By means of these wells, the level of water table, the temperature of ground-water and quantities of contained salt

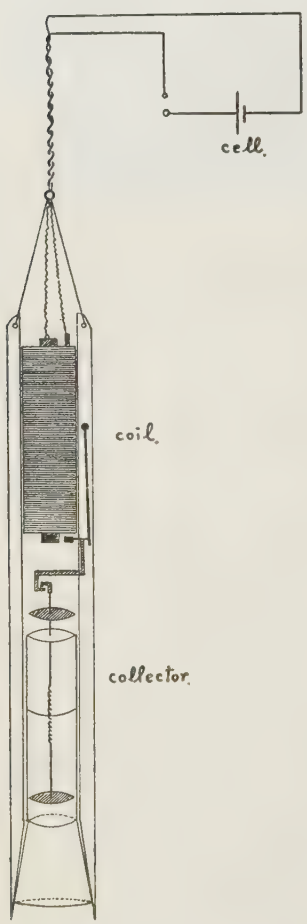
Fig. 2



are to be measured. As the soil is sandy, the iron pipes could be driven directly into ground to a depth of within 30 or 40 metres. But, for the deeper well we had to insert iron-pipes after boring with "Kazusa-bori". Some of the iron-pipes used were ordinary ones, but others were set up with many holes specially arranged around the periphery, and their sharp ends were provided with numerous smaller holes and wrapped round with wire-gauze, etc.

(i) *Method of boring.* Generally the iron-pipes are driven in by a boring weight (about 25 kgs.) and after every one or half metre of driving a sucker is inserted, the internal water and soil are sucked out, and then the pipes are driven in again, and so on. The sucker is a cylindrical tube made of corrugated iron, 1.2 inches in diameter and about 2 metres long, having a leather valve at the lower end. When we insert it in the iron-pipe and oscillate it up and down, it absorbs the water and soil in the lowest portion of the well. The iron-pipes, with small holes at the ends or wrapped round with wire-gauze, are used generally for shallow wells within 10 metres' depth and water is taken out by a pump every half metre. Thus we can save the trouble of inserting a sucker, but is is difficult to drive pipes deeper by this method.

Fig. 3



As the "Kazusa-bori" is a method of boring, always filling up the hole liquid clay and preventing collapse by the balancing internal pressure, it is impossible to measure the salinity of the ground water while at work as in the driving method. It is a method, however, that has been used from ancient times for deep boring, so we tried it to see whether it would suit our experiments.

(ii) *Method of measurement of contained salt.* The salt contained in the ground-water can be easily measured by silver nitrate titration. The only difficulty is to collect the water from any depth

within the iron-pipe of 2 inches diameter without disturbing the water. For this purpose, we constructed a special small collecting bottle, as shown in Fig. 3. This is made of metal, 35 cms. in whole length, 3 cms. in outward diameter, and its upper half portion is iron cored coil 10 cms. long, 2 cms. in diameter, and its lower half constitutes a cylindrical collector 15 cms. long and 2 cms. in inner diameter. We open the upper and lower lids by means of a spring in the centre, and suspend both poles of coil from the top with two rubbered wires. After having lowered it to the desired depth in the well, a circuit is made with a dry cell, when the two lids close simultaneously by action of the spring. When the water-bottle is opened, the water can pass freely through it, and therefore if the lowering of the bottle is done very slowly, it is possible to collect water at any depth, practically without disturbing it. The quantity of water taken in by this instrument at a time is 50 c.c., and this is sufficient for examination of the contained salt.

(iii) *Method of measuring temperature of ground-water.* In a two inch pipe, of course, an ordinary marine thermometer cannot be used. Hence we measured the temperature by the variations of electrical resistance of copper wire, and also by a platinum resistance thermometer. But in order to take a large number of measurements quickly, it was most convenient to use non-sensitive mercury thermometers, and for measuring the water-temperature only we often used ground-thermometers.

(iv) *Method of measuring level of water table.* To determine exactly the level of the water-table within the iron pipes, we used the sensitive limnimeter which we had constructed and used many years ago when we investigated the underground flow in the bed of River Hino, Tottori. Its construction was explained by Prof. Nomitsu[1] in the report of Nippon Gakujutsu Kyokai Vol. 4. Of course, the mutual heights of the upper ends of the observation wells were determined by ordinary levelling.

(v) *Additional investigation.* As it is neccessary for us to know the variation of sea-level, salinity and temperature of sea-water etc. in the outer sea, and the variation of the water table by precipitation during the executive term of observation, we set up a tidal-well near the sea-shore and put Richard's self-recording limnigraph in it, and observed the sea-level. The observations of the temperature and salinity

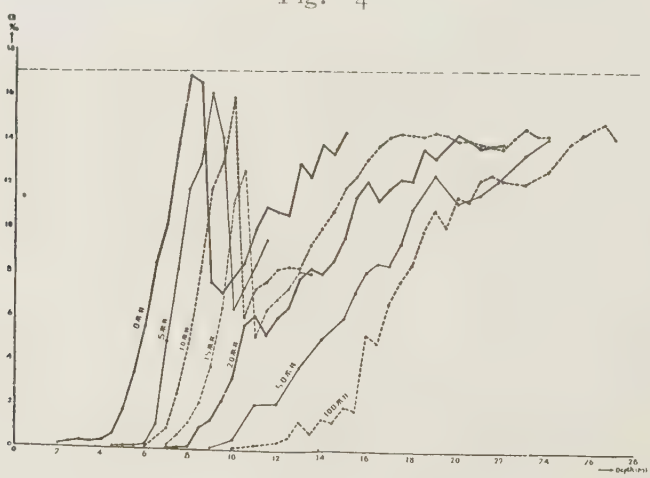
1. T. Nomitsu, On the measurement of quantities of underground-water. (Japanese) Rep. of Japanese Association for the Advancement of Science. **4**, 79 (1928).

of the coastal sea-water, and the variation of the water table in the wells were made at a fixed time every day. In order to investigate the hydrological character of sands under the ground, we collected samples of soil of about one litre at every one or half metre of boring for each observation well.

§ 4. Results of Experiments

(i) *Investigation of contained salt in the ground-water.* After we had tried various methods of boring the observed wells and compared their efficacy, we used the driving method for the most part near the shore. The results of determination of the contained salt at each depth of the observation wells, are shown in Table 1, and illustrated in Fig. 4.

Fig. 4



These figures (Table 1) show that the state of salinity near the shore differs greatly from that at some distance out, and that as to the former, the deeper we dig, the more the salinity increases, rapidly at first, and after momentary rapid decreases in the middle, slowly increases again. Indeed a most peculiar phenomenon! On the contrary, at some distance from the shore, the salinity increases slowly but steadily, after salt has been detected. When we investigated the rate of increase of salinity in further detail, almost similar states were found in 0 m, 5 m, 10 m and 15 m wells[1], and the rate of increase of Cl was almost 5‰

1. Name of observation well shows by the distance from original bench to landward. For example, 15m well is a well 15 metres distant from the original bench on the strand line.

Table 1

No. of Well. / Distance. / Depth.	I. 0m	II. 5m	III. 10m	IV. 15m	V. 20m	VI. 50m	VII. 100m
m	%						
0.0	0.050	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.074	0.000	0.000	0.000	—	—	—
1.0	0.074	0.000	0.000	0.056	0.000	0.000	0.000
1.5	0.074	0.000	—	0.056	—	—	—
2.0	0.099	0.000	0.000	0.056	0.000	0.000	0.000
2.5	0.124	0.023	—	0.056	—	—	—
3.0	0.310	0.023	0.025	0.084	0.056	0.000	0.000
3.5	0.248	0.023	—	0.056	—	—	—
4.0	0.285	0.047	0.025	0.056	0.056	0.000	0.000
4.5	0.558	0.047	—	0.056	—	—	—
5.0	1.737	0.047	0.050	0.056	0.056	0.000	0.000
5.5	3.329	0.070	—	0.084	—	—	—
6.0	5.522	0.117	0.124	0.056	0.056	0.000	0.000
6.5	8.395	1.049	—	0.112	0.056	—	—
7.0	10.087	4.839	0.869	0.112	0.056	0.000	0.000
7.5	13.720	8.104	2.482	0.629	0.056	—	—
8.0	16.853	11.718	4.703	1.258	0.140	0.000	0.000
8.5	16.515	12.826	8.067	2.097	0.923	—	—
9.0	7.518	15.974	11.765	3.775	1.258	0.073	0.024
9.5	6.892	13.934	12.894	6.291	2.083	—	—
10.0	7.706	6.238	15.823	11.184	3.215	0.545	0.120
10.5	8.270	7.229	5.932	12.512	5.550	—	—
11.0	9.874	8.277	7.267	5.018	6.053	2.024	0.252
11.5	10.901	9.386	7.518	6.221	5.103	—	—
12.0	9.771		8.145	6.710	5.928	2.109	0.361
12.5	9.503		8.207	7.269	6.361	—	0.577
13.0	12.753		8.270	8.178	7.703	3.721	1.298
13.5	12.290		9.147	7.983	8.111	—	0.793
14.0	13.810		9.948		7.924	5.006	1.418
14.5	13.304		10.769		8.528	—	1.310
15.0	14.254		11.794		9.602	5.963	1.983
15.5			12.307		11.415	7.139	1.911
16.0			13.012		12.154	8.072	5.229
16.5			13.653		11.201	8.508	4.808
17.0			14.166		11.778	8.399	6.683
17.5			14.358		12.221	9.345	7.609
18.0			14.230		12.288	10.934	8.474
18.5			14.166		13.658	—	9.844
19.0			14.294		13.108	12.406	10.854
19.5			14.294		—	—	10.181
20.0			13.974		14.249	11.064	11.295
20.5			13.974		—	—	11.281
21.0			13.846		13.618	11.511	12.191
21.5			13.717		—	—	12.418
22.0			13.589		13.819	12.100	12.358
22.5			14.102			—	—
23.0			14.487			13.371	12.032
23.5			14.230			—	—
24.0			14.230			14.006	12.684
24.5							—
25.0							13.940
25.5							—
26.0							14.581
26.5							14.726
27.0							14.134

per metre for the first 10 metres approximately. Namely, at about 3~4 metres depth after salinity first began to increase, almost the same salinity as in the outer sea was reached, and after further boring, the salinity decreased rapidly to 1/3 the maximum value, then increased again at a rate 1.5 ‰ of Cl per metre, down to the 20 metre stratum. Analogous rates of increase were found for 50 m and 100 m wells. As we detected salt near the 10 metre stratum for both of these wells, we knew that the condition was same in depth below 10 metre under the water table, whether near the distance from the shore. Thus the conditions of increasing salinity are divided into two quite different sorts, with a boundary at 10 metre or so, the increasing rate in the upper stratum being about three times that in the lower, and 20 m well in the middle in place has both characteristics. At depths greater than 20 metres in all observation wells, the rate of increase decreased gradually, and the salinity approached asymptotically that of the open sea. Thus, it seemed likely that the decrease of salinity near the ten metres stratum depends upon the nature of the soil. When we investigated the collected sands, the stratum in which salinity decreased rapidly was the layer in which fine sands turned to Hedro-stratum[1]. As the boring of this stratum wanted twice or thrice the time necessary for sand stratum, it would appear that the stratum is semi-impervious. The organization of the salinity distribution in such a semi-impervious stratum is a problem for future study. Moreover, the salinity in the upper part of the ground-water by the observation well nearest the coast line was very slight down to 4 metres below the level of water, and beyond 4.5 metres it increased suddenly; i. e. the contained Cl was 0.31‰ (S=0.63‰) at 4 metres' depth, i. e. the same order as common river-water, and the water can in practice be supplied as fresh-water for drinking purposes. In the immediate vicinity of the shore there exists a fresh-water layer several metres thick, a phenomenon that presents a considerable difference from prevailing ideas on a subject of which there have been few exact investigations.

I believe that this result will supply material not only for scientific hydrology but also for the more practical subject of drinking water in coastal regions.

(ii) *Observation of water-table and levelling.* It is an important

1. Hedro is the local name of a sandy slime or silt, and consists of fine sand 40% and subclay 40% besides other ingredients.

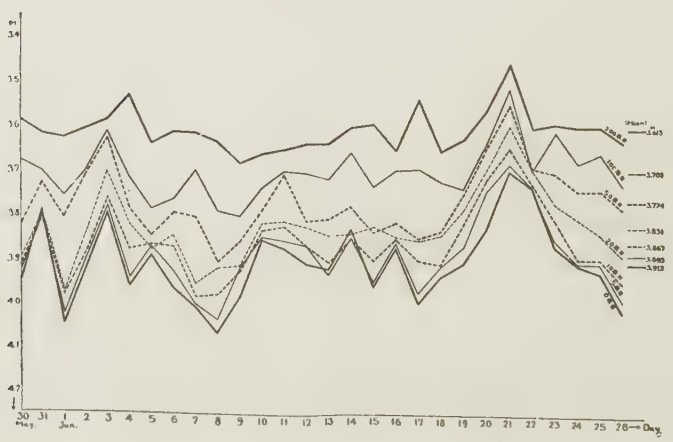
part of this investigation to determine the exact shape of the water table. As it constantly changes by virtue of rainfall and other factors, it is not so simple to decide level difference among the observation-wells. Wells near the shore are specially influenced by tidal action, and the effect differs in amplitude and phase according to the distance from the sea-shore, so that for the present purpose the relative levels cannot be obtained merely by simultaneons levelling. We must determine the shape of the water table on an average condition. At the coast under consideration, the daily amplitude of tide, though small, is 15 cms. on average, and the irregular rise and fall of the sea level, in a period of several days, happens to be 70 cms. These actions some what degree decrease within the sand stratum, but in order to determine the level difference of a few cms. order among the observation wells dear the shore, we must contrive some means to exclude the influence of fluctuation of the sea-level. For this reason, in three wells specially set up near the shore and another well 200 metres distant away from the shore, we observed the ground-water level over a period of about half a month by simple measurement with a long rule and a weight. The result showed that, during our observation, the range of variation of the ground-water itself, was 50~60 cms. near the shore, but was 18 cms. at the point 200 m. away from the shore; i. e. irregular fluctuation of the sea level, having a period of several days, gave no small influence near the coast. But, this influence of irregular fluctuation would be eliminated by taking many days' continuous observation. The influence of the regular tide near the shore can be excluded in greater part, if we fix the observation time every day during a long term. Therefore, we drove new two-inch iron-pipes for observation of water-level at eight points situated at 0, 5, 10, 15, 20, 50, 100, 200 metres distance from the original bench-mark on the strand, and took observations continuously with our accurate limnimeter at a fixed time every day for about a month.

We were afraid that the observation well might move up or down during our observation term, so we set up bench marks (5 inch wood piles plugged with concrete) beside each well. To measure the level difference between each well top and the upper surface of corresponding bench mark we used Bamberg's Level, and we made levellings twice off and on. In the middle of the observation an accident occurred to the 15 metre well and the well became useless. The observed results for the other wells are shown in Table II. and in Fig. 5.

Table II

No. of Well. / Distance. / Date.		I. 0m	II. 5m	III. 10m	V. 20m	VI. 50m	VII. 100m	VIII. 200m
		m						
May	30	3.950	3.928	3.912	3.899	3.826	3.678	3.587
	31	3.794	3.805	3.801	3.796	3.729	3.707	3.619
Jun.	1	4.052	4.027	3.988	3.976	3.810	3.760	3.630
	2	3.930	3.909	3.892	3.850	3.714	3.710	3.609
	3	3.792	3.776	3.764	3.706	3.627	3.613	3.591
	4	3.963	3.947	3.878	3.822	3.789	3.718	3.532
	5	3.894	3.875	3.870	3.876	3.852	3.792	3.648
	6	3.969	3.931	3.874	3.849	3.801	3.768	3.620
	7	4.013	4.006	3.991	3.961	3.809	3.702	3.623
	8	4.073	4.039	3.983	3.923	3.911	3.795	3.641
	9	3.988	3.930	3.930	3.920	3.868	3.806	3.688
	10	3.858	3.852	3.841	3.822	3.800	3.744	3.670
	11	3.880	3.861	3.829	3.820	3.717	3.705	3.659
	12	3.911	3.877	3.874	3.832	3.820	3.713	3.647
	13	3.922	3.938	3.913	3.848	3.811	3.727	3.645
	14	3.839	3.854	3.855	3.847	3.786	3.664	3.606
	15	3.968	3.954	3.905	3.830	3.838	3.738	3.601
	16	3.872	3.865	3.856	3.851	3.814	3.702	3.660
	17	4.002	3.983	3.901	3.860	3.854	3.700	3.647
	18	3.941	3.922	3.917	3.850	3.839	3.732	3.661
	19	3.910	3.876	3.826	3.792	3.762	3.746	3.634
	20	3.833	3.748	3.725	3.701	3.651	3.643	3.570
	21	3.702	3.690	3.654	3.604	3.553	3.525	3.466
	22	3.742	3.741	3.736	3.703	3.701	3.709	3.611
	23	3.873	3.862	3.818	3.780	3.708	3.618	3.602
	24	3.912	3.907	3.897	3.812	3.749	3.688	3.608
	25	3.929	3.912	3.900	3.846	3.750	3.667	3.609
	26	4.018	3.996	3.952	3.893	3.789	3.740	3.642
Mean.		3.912	3.893	3.867	3.831	3.774	3.708	3.615

Fig. 5



(iii) *Observation of temperature of the ground-water.* In order to determine the specific gravity of ground-water we must measure its temperature as well as its salinity. Therefore, we previously arranged to measure the temperature at the same time as the salinity. But the measurement of the temperature compelled us to stop boring for the time being, which was not necessary in determining the salinity. This, however, interfered with the progress of operations, and moreover, in regions deeper than 5 or 6 metres, the variation of temperature is very small. We therefore put a ground-thermometer after sunset into the lowest portion reached at the end of the day's boring, and read it before commencing operations next morning. Table III shows the temperatures observed by this method.

Table III

Well.	Depth.	Temperature.	Date.
	m	°	
0 m	2.0	15.6	May 7
	7.0	13.0	„ 8
	10.0	13.2	„ 9
	12.5	13.3	„ 10
	16.0	13.1	„ 11
		13.65 (mean)	
5 m	6.0	13.6	May 26
	12.0	13.1	„ 27
		13.35 (mean)	
10 m	7.0	12.9	May 6
	11.0	13.5	„ 7
	12.0	13.4	„ 8
	15.0	13.4	„ 9
	21.0	13.9	„ 19
	26.0	13.6	„ 20
		13.45 (mean)	
15 m	5.0	13.4	May 27
	11.0	13.6	„ 28
	16.0	14.0	„ 29
		13.67 (mean)	
20 m	11.0	13.4	May 28
	15.0	13.2	„ 29
	24.0	13.4	„ 30
		13.33 (mean)	
50 m	8.0	13.6	Nov. 22
	11.0	13.7	„ 23
	15.0	13.4	„ 30
	19.5	13.5	Dec. 3
	21.5	13.7	„ 4
	26.0	13.3	„ 6
		13.57 (mean)	
100 m	4.0	14.3	Oct. 17
	7.0	14.1	„ 19
	22.0	13.5	„ 26
	27.0	13.2	Dec. 4
		13.78 (mean)	
200 m	20.0	13.7	Nov. 14
	30.0	13.9	„ 18
	50.0	14.2	Dec. 3
		13.93 (mean)	

From the vertical distribution of temperature in each well, we see that the variation of temperature of the part deeper than 5 or 6 meters is of the same order as the observation-error; only in the 200 m well, bored deepest, the temperature indicated a slight rise in

the deep stratum. The vertical average temperature of each well is about 13°, and the total average is 13°.60.

(iv) *Observations of salinity and temperature in the open sea.* If the ground is completely pervious, the salinity in the deep stratum should agree with that of the open sea. Moreover, in order to determine the specific gravity of sea-water its temperature must be known. Hence we observed temperature and salinity of the coastal sea-water once a day during the operational period. Mean salinity and mean temperature of sea-water and mean specific gravity calculated from these data are as follows :—

Observation period.	Quantities of (Cl).	Temperature. (θ)	Specific gravity. (σ_t)
Oct. 12~Oct. 28	17.495‰	20°.84	21.99
Nov. 12~Dec. 5	17.414	16.09	23.02
May 5~Jun. 26	17.017	19.07	21.78

Especially, mean values during investigation of boring near the coast (May 5^{th}~28^{th}) are Cl=17.03‰ θ=18°.02 σ_t=22.06. The quantities of contained chlorine in the table above are those of coastal sea-water; and a sectional observation in the front offing shows us that the quantities increase 1‰ or so.

§ 5. Comparison with Our Theory

Let us now compare the results of experiments with our theory.

(i) *The upper boundary of fresh-water layer.* The theoretical formula for the upper boundary of fresh-water is

$$y^2=h_0^2+\frac{h_L^2-h_0^2}{L}x \qquad \text{.....(3)}$$

The mean water-level in each well reduced from Table II, taking a standard surface near the sea-level and measuring y vertically upwards, is as follows :

Distance from the coast (x)	m 0	5	10	20	50	100	200
Water level from standard surface (y)	m 0.030	0.049	0.075	0.111	0.168	0.234	0.327

There is a level difference of 29.7 cms. between 0 m. well and 200 m. well. Now using the values of only these two wells, let us determine the shape of the upper boundary from the above formula.

$h_0=0.030$, $h_L=0.327$ and $L=2000$ $\therefore$ $y^2=0.009+0.000530\,x$ ...(4)

If we calculate the water-levels of other wells from this theoretical equation (4) and compare the results with the observed values, a very fair coincidence will be seen, as shown herewith:

Distance x	m 0	5	10	20	50	100	200
Calculated y	m 0.030	0.060	0.079	0.107	0.166	0.232	0.327
Observed y	0.030	0.049	0.075	0.111	0.168	0.234	0.327

Further, the empirical formula obtained by Least Square, using the observed values of the above-mentioned seven wells, agrees with the theoretical equation (4) very well, as shown below:

Empirical formula $y^2=0.000854+0.000533\,x$

Theoretical formula $y^2=0.000900+0.000530\,x$

(ii) *The lower boundary of fresh-water layer.* (Contact surface of fresh- and salt-water) The theoretical formula for the lower boundary may be transformed into the following formula from equations (2) and (3)

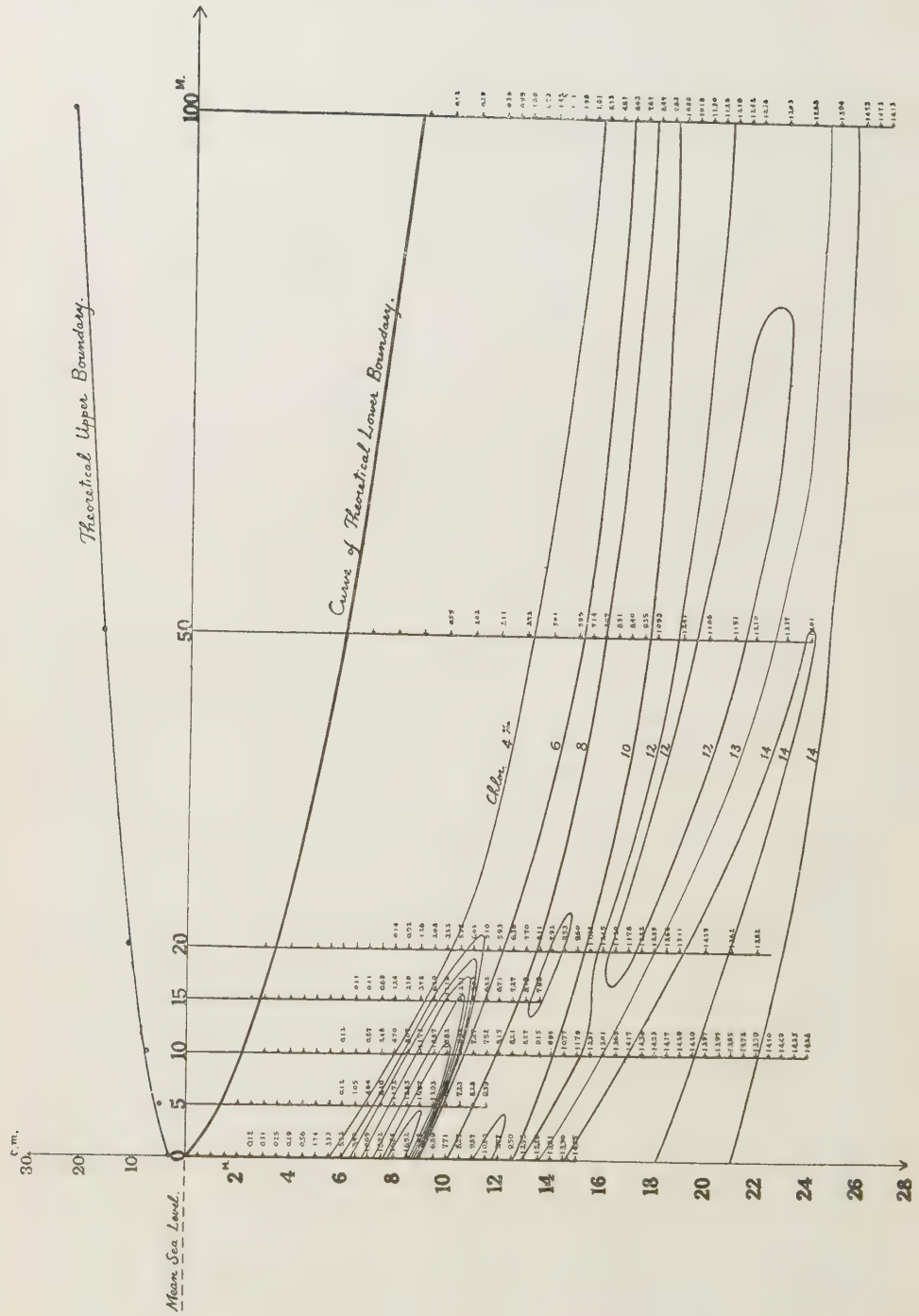
$$y'=\frac{\rho_0}{\rho-\rho_0}y \qquad \text{.....(5)}$$

Using the mean salinity in the open sea Cl=17.03 ‰ and the average temperature of the ground-water $\theta=13.60$, we get the specific gravity in situ $\rho=1.02303$ as $\rho_0=1$, and formula (5) becomes $y'=43.42y$

$\therefore$ $y'^2=1.6968+0.0999207\,x$ .....(6)

This is the theoretical curve obtained by means of the water-levels of wells at both ends and by the specific gravity of fresh- and salt-water under the ground. On the other hand, the sectional-diagram of the actual distribution of salinity is as in Fig. 6.

Owing to the Hedro stratum (Semi-impervious) which exists at about 10 metres' depth, the distribution of salinity is quite different at its upper and lower extremities; and though we cannot determine the lower boundary of the fresh water as distinctly as the upper, the shape of the isohaline is very similar to the curve which is given by theoretical formula (6), that is the thick line in the figure. If there is no Hedro stratum and the whole is sand, the isohaline may crowd, and probably the lower boundary will resemble the line shown as Cl=6 ‰ in the figure. If we put the theoretical curve over it, it nearly coincides. In addition, we notice that every isohaline shows a tendency to rise for the 100 m. well, as compared with the theoretical curve.


Theoretical upper Boundary.
Curve of Theoretical Lower Boundary.
Mean Sea Level.
c.m.
m.
Chl. 4 ‰

§ 6. Conclusion

According to the above results, our theoretical view of the coastal ground-water based on hydrodynamical considerations was ascertained to hold good for the actual sea-shore as well as in model experiments. Moreover, we found that the fresh-water layer may sometimes be 4 metres thick, even at the actual coast line. Besides, we met several other noticeable facts relating to the condition of diffusion of salt near the contact surface of both layers, the peculiar distribution of salt due to a semi-impervious stratum, and the effect of ununiformity of hydrological character of sand stratum, etc. Studies of these problems will be reserved for some later days after careful examination of the 300 soil samples collected during the experiments.

In conclusion, the author wishes to express his sincere thanks to Nippon Gakujutsu Shinko-kwai for the grant given towards the expenses of this study, and to Prof. T. Nomitsu for his kind guidance throughout the work, and also to Messrs. H. Habu, T. Matsuzaki and K. Yamashita for their assistance in the laborious measurements.

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